Towards adaptivity in 3D Robot Vision performance optimisation

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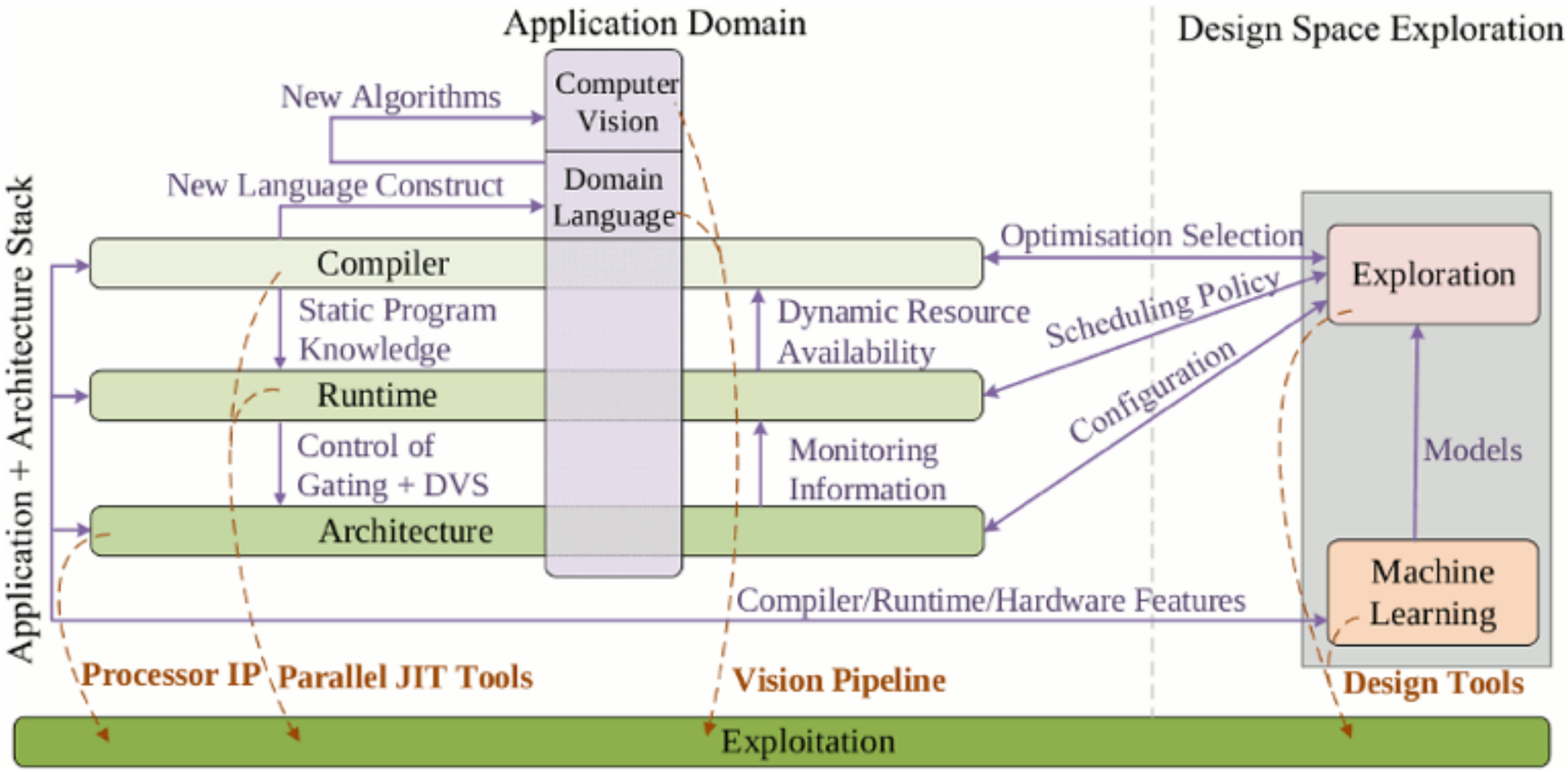
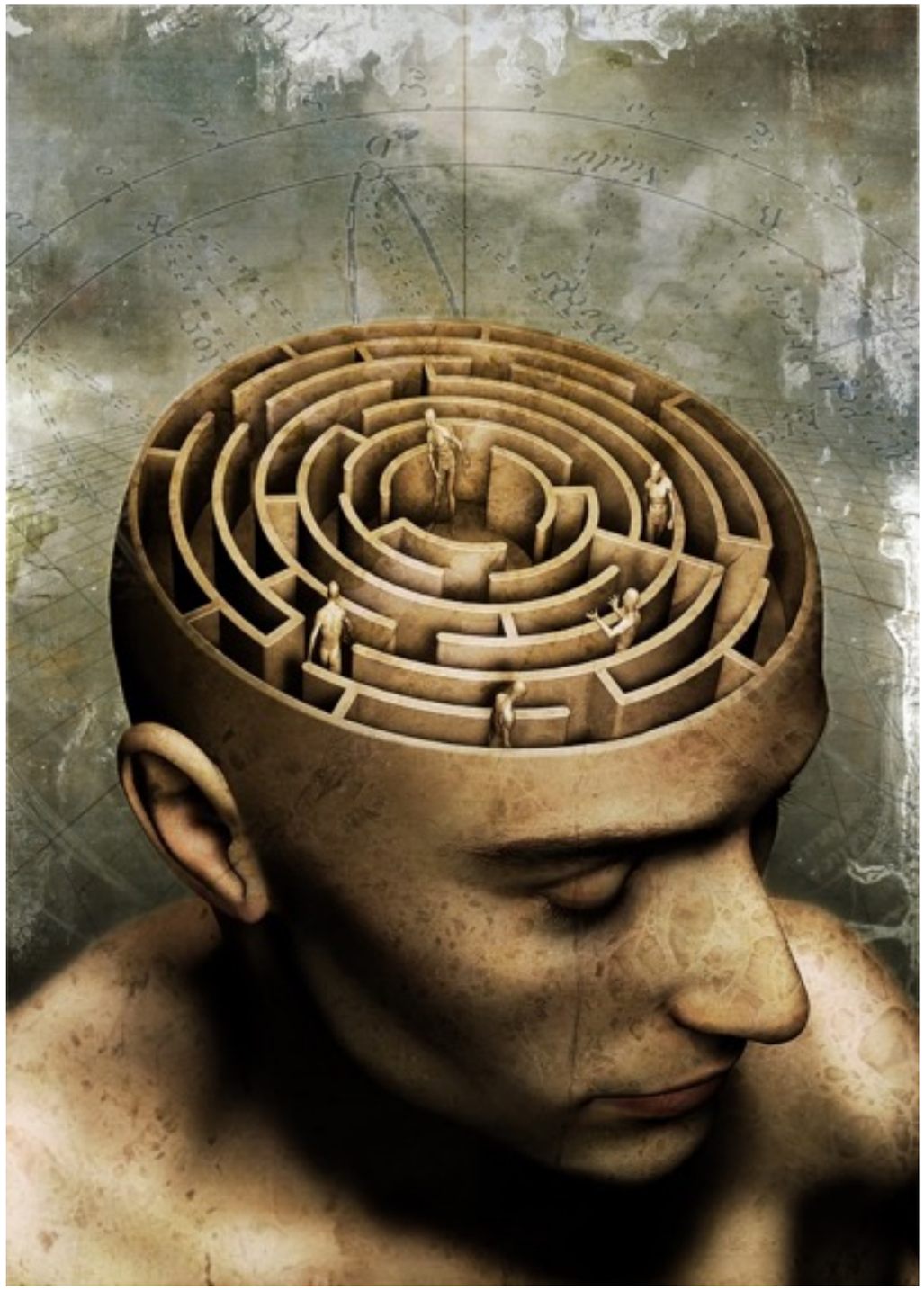
PAMELA project

Panoramic Approach to the Many-corE LAndscape - from application to end-device: a holistic approach



Outline

- **The SLAM application, a brief introduction**
- “Performance” benchmarking methodology
- Space exploration of algorithmic and implementation design choices



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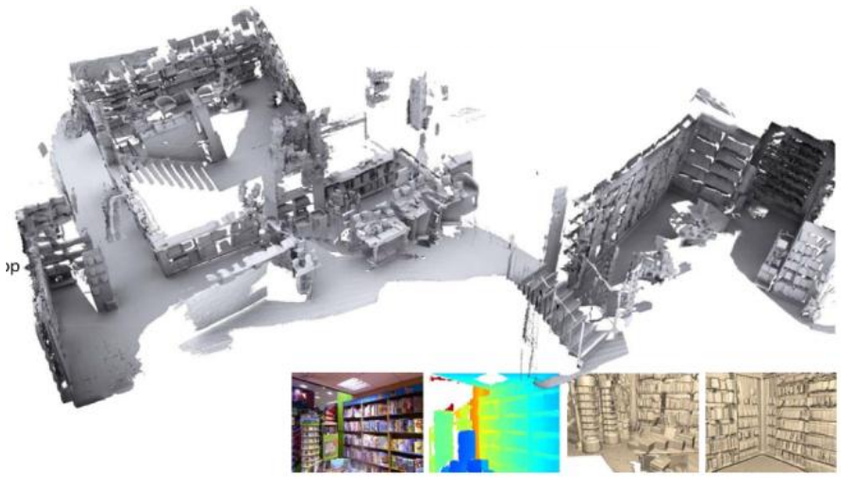
The three R's of vision: Spectrum of Computer Vision Research

Reconstruction

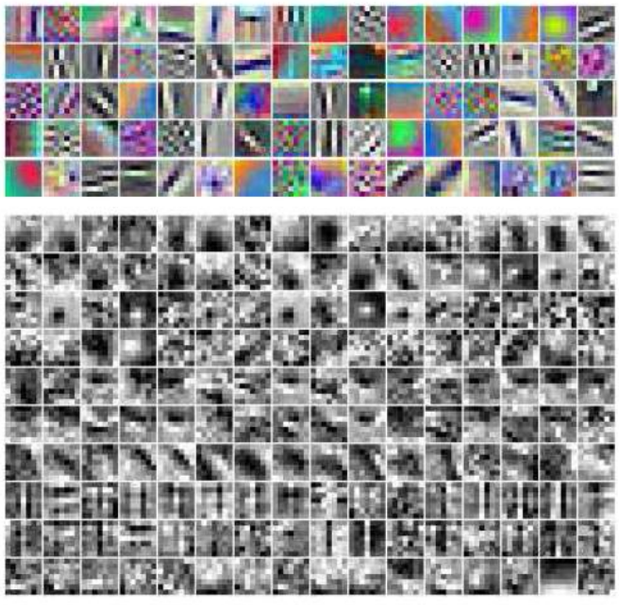
Scalable Kinect Fusion (2013)

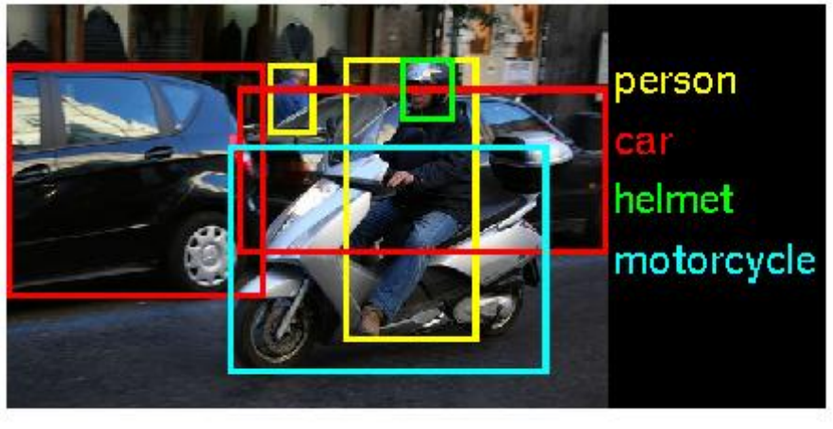


Building Rome on a cloudless day (2010)

Recognition

Deep learning for scalable Object class detection (2014)





Reorganisation or Grouping

Contour detection and segmentation (2011)

Credit: Zeeshan Zia

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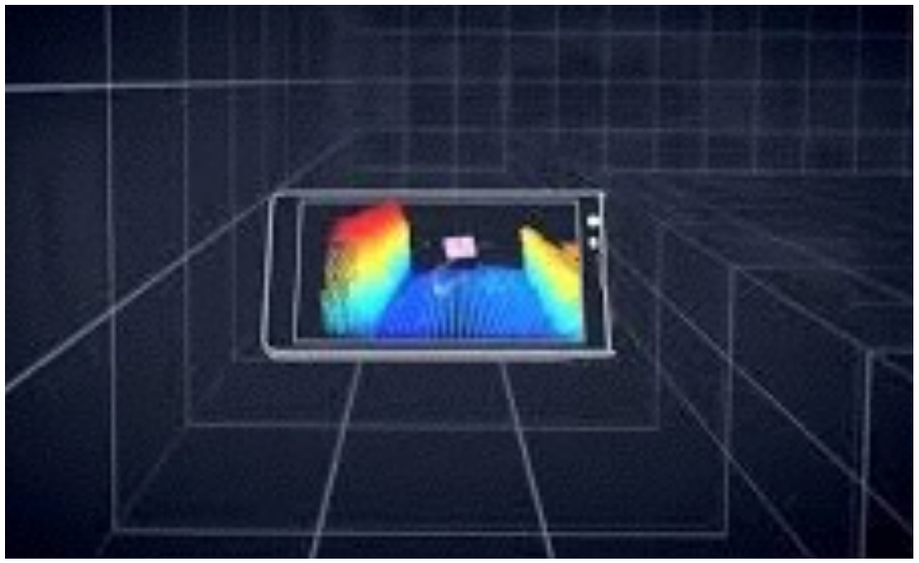
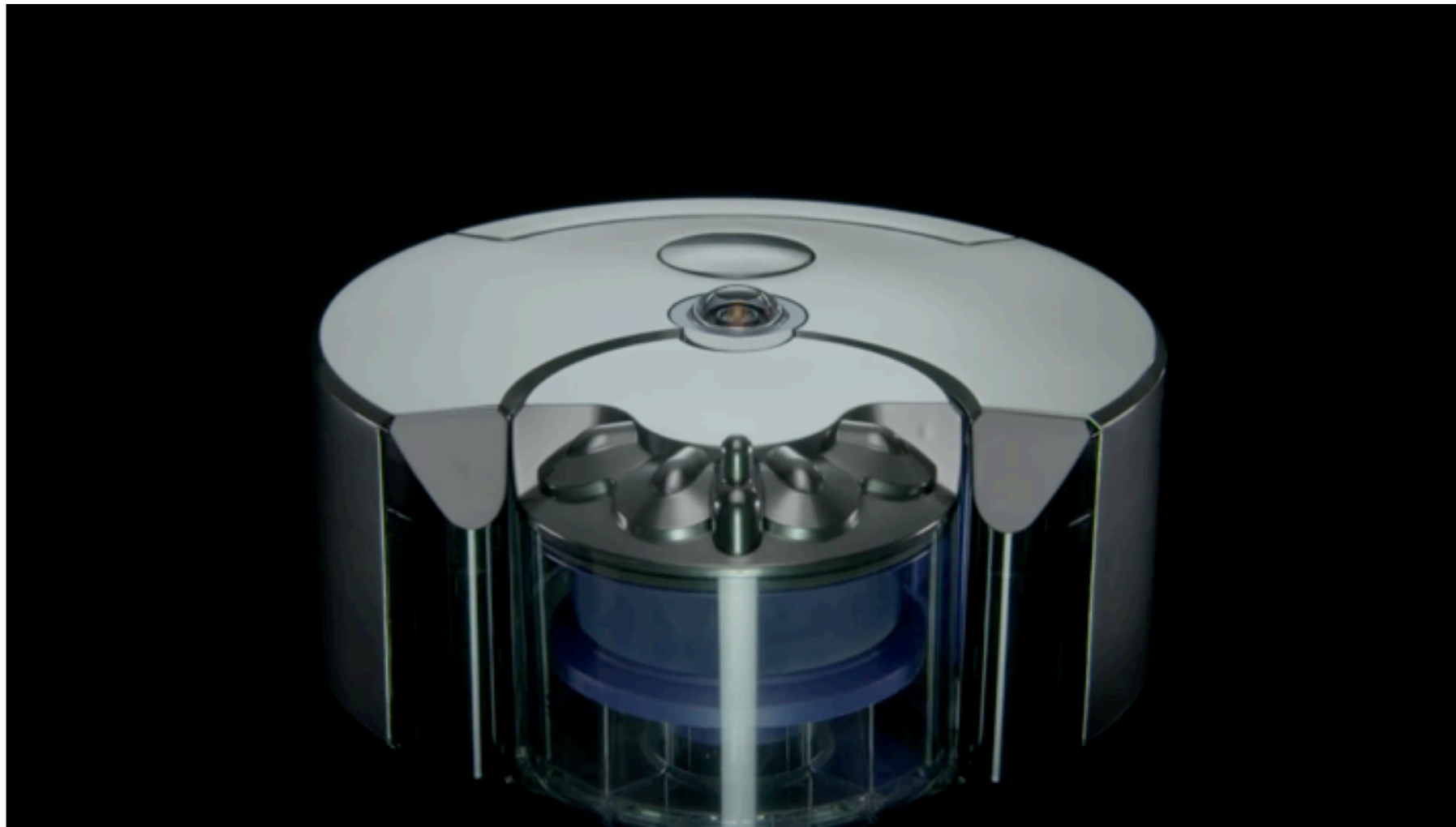
Simultaneous localisation and mapping (SLAM)

Build a coherent world representation and localise the camera in real-time

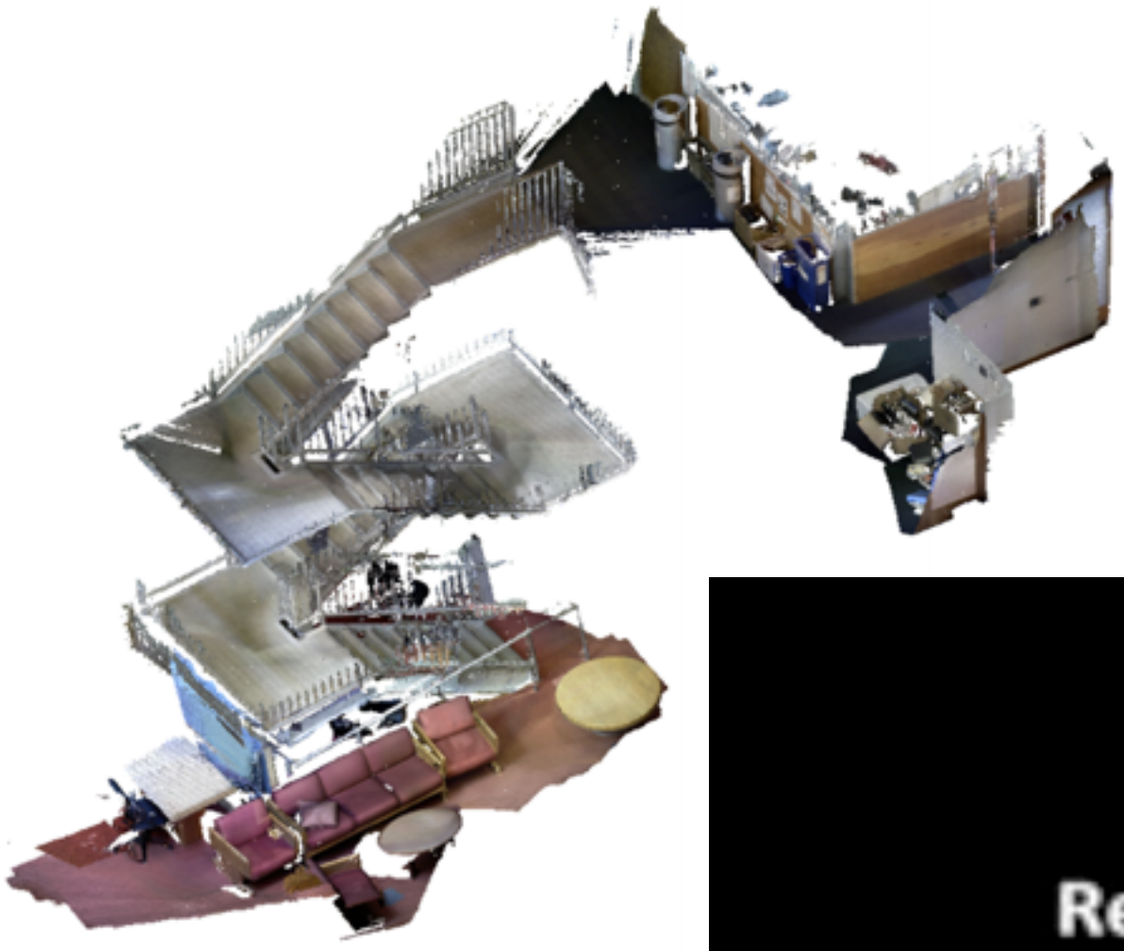
Sparse SLAM





Video:
Dyson 360 Eye

Simultaneous localisation and mapping (SLAM)

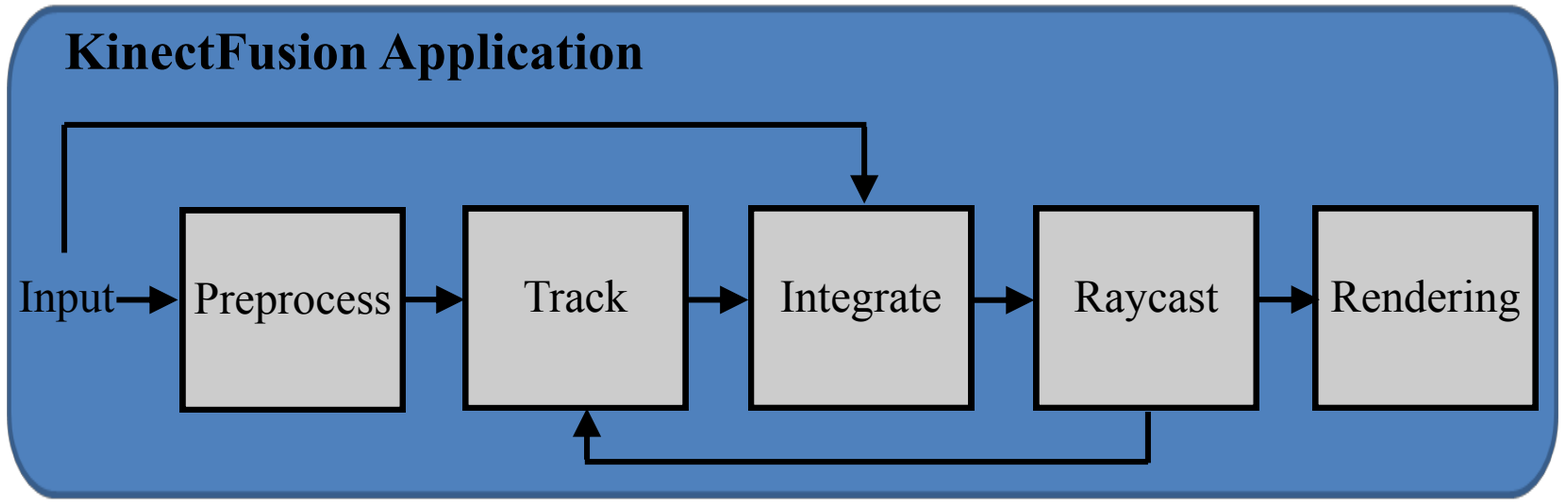


[Whelan et al. 2012]

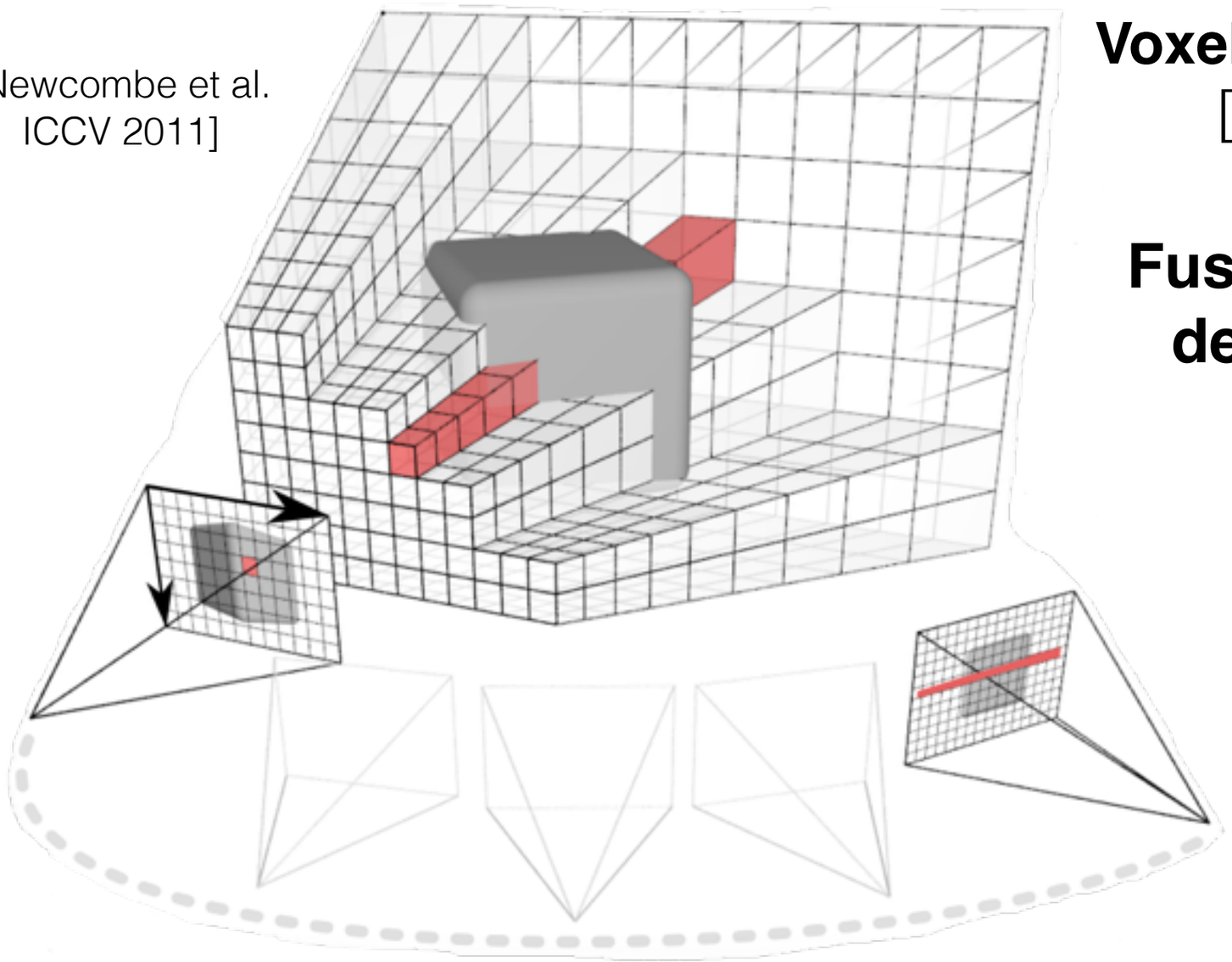
Dense SLAM

Video:
[Newcombe et al. ISMAR 2011]

KinectFusion SLAM implementation



[Newcombe et al. ICCV 2011]



Voxel grid represents **3D surfaces**
[Curless and Levoy 1996]

Fuses (or integrate) the stream **depth frames** into a **3D map**

3D surfaces recovered by **raycasting**

Localisation (or tracking): estimates the camera pose

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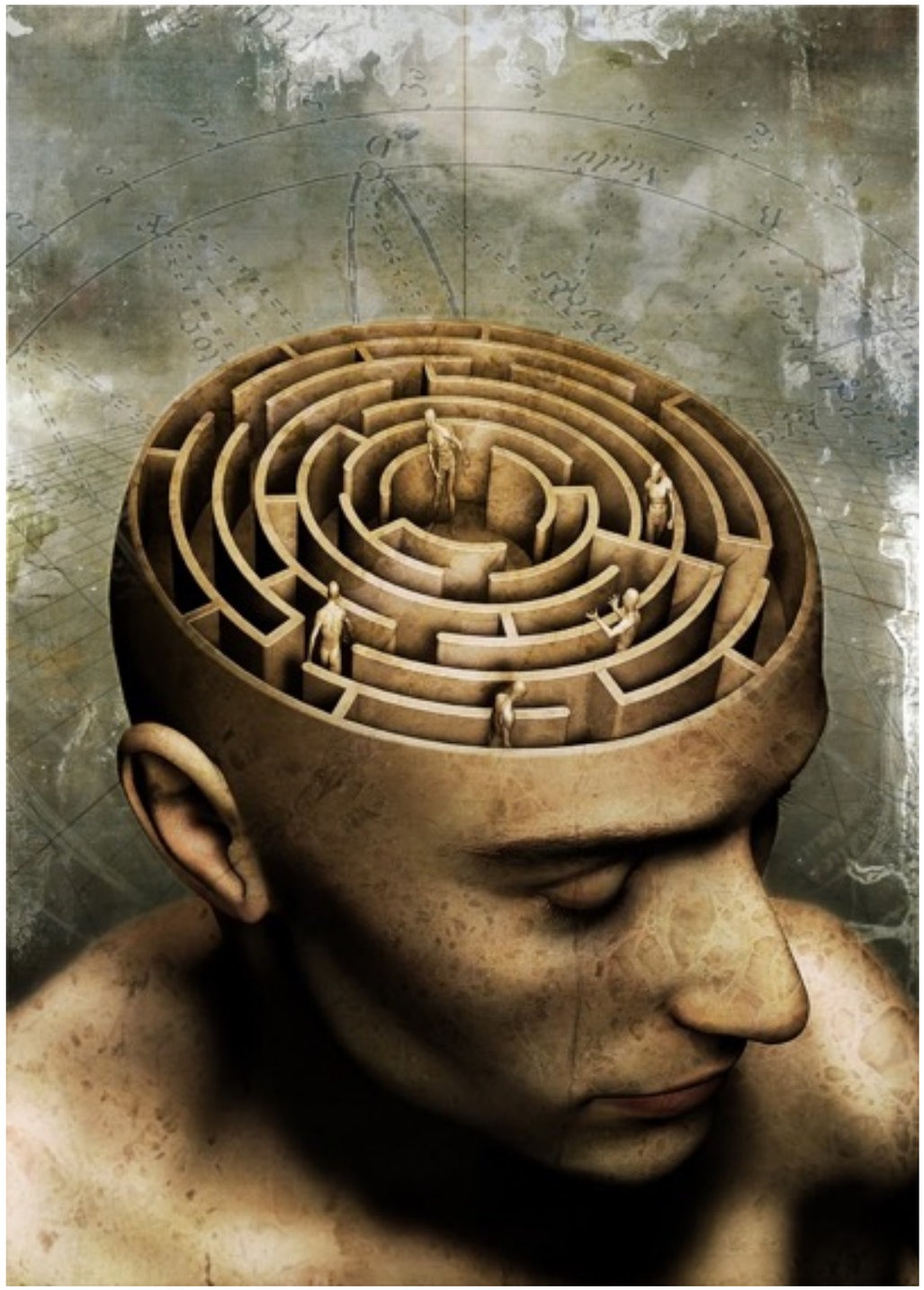


What is “Performance”?

1. In several domains performance is **execution time**
2. In some domains performance is **accuracy**
3. What about **energy**?
4. But also memory consumption, temperature, robustness, etc.

A modern system evaluation considers multiple metrics:

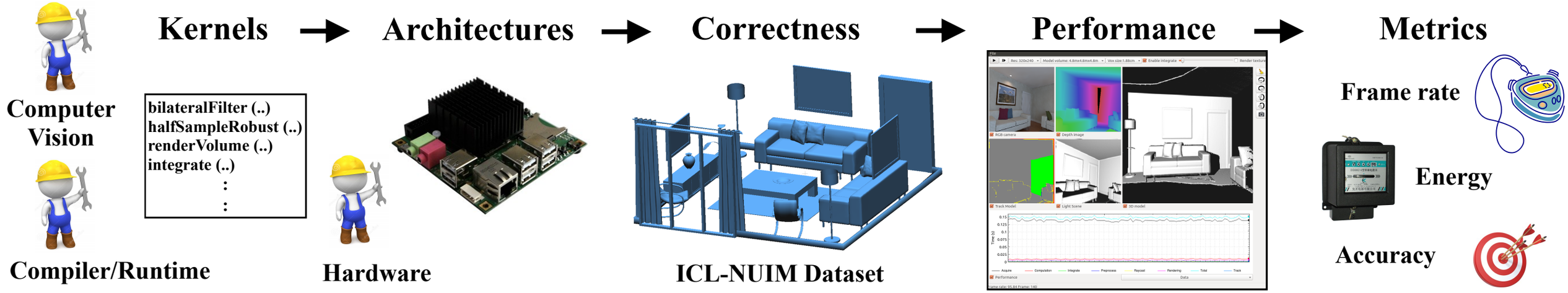
$$Performance = \begin{bmatrix} Runtime \\ Energy \\ Accuracy \end{bmatrix}$$

This defines a multi-objective optimisation problem: trade-off

Three “Performance” metrics

Holistic approach to SLAM “performance”:

SLAMBench



A publicly-available benchmarking framework for quantitative, comparable and validatable experimental research to investigate trade-offs in performance, accuracy and energy consumption of a SLAM system

How to measure SLAM "Performance"?

SLAM computation depends on:

- Images acquired
- Way the camera is moved
- Numerical approximations
- Processing frame rate (depends on hardware capability)

Need for reproducibility and accuracy check
Pre-recorded scenes
Process-every-frame mode
ICL-NUIM and TUM RGB-D datasets

ICL-NUIM dataset

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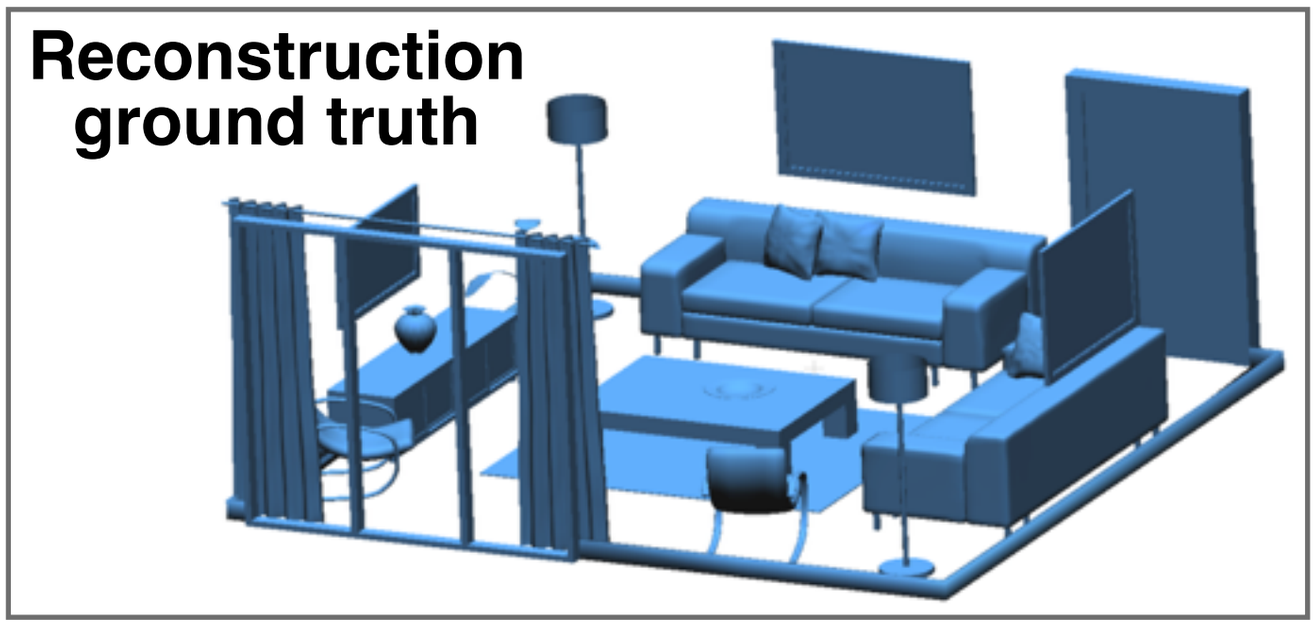
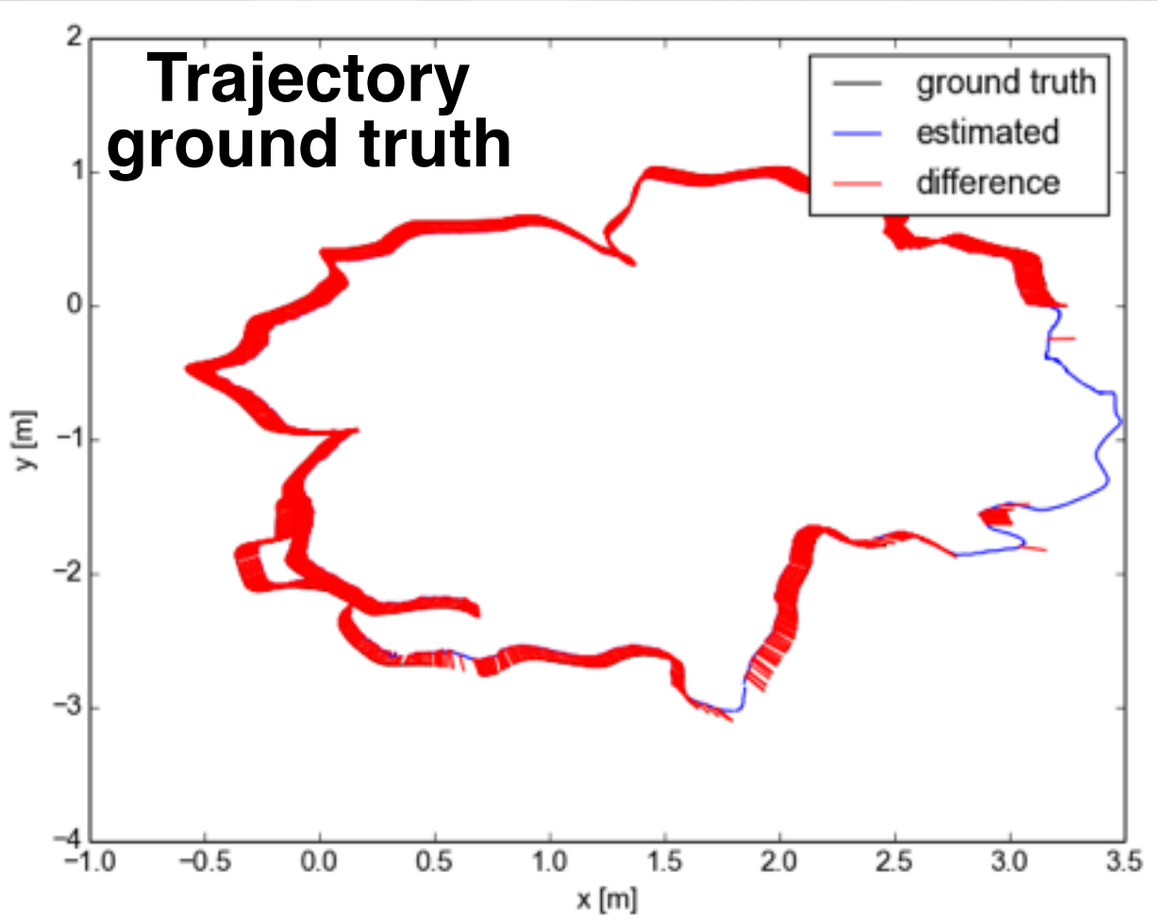
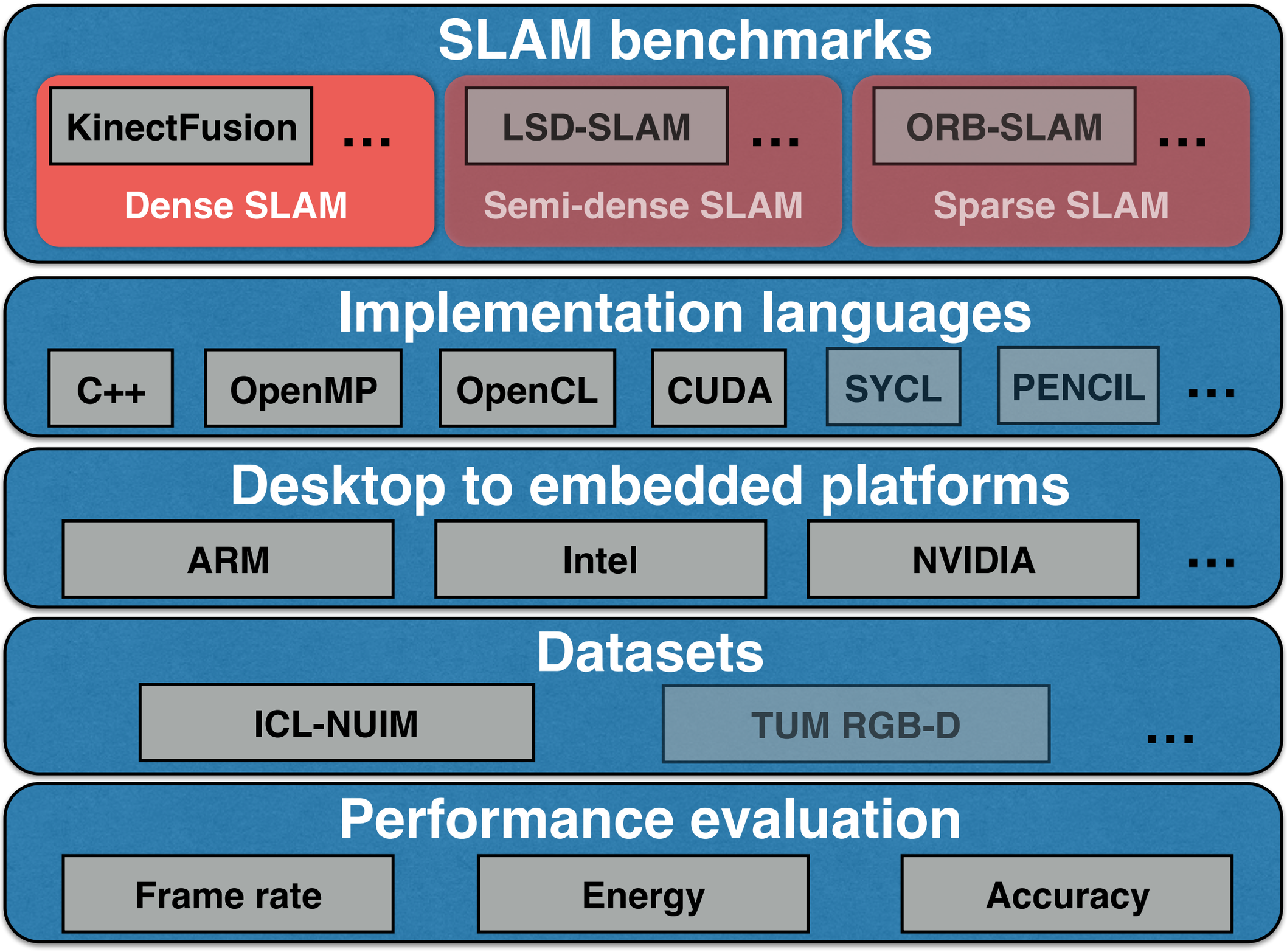




- ICL-NUIM synthetic dataset [Handa et al. 2014]
- 880 RGB-D frames at 30 FPS
- Absolute trajectory error (ATE) based on ground truth

SLAMBench framework



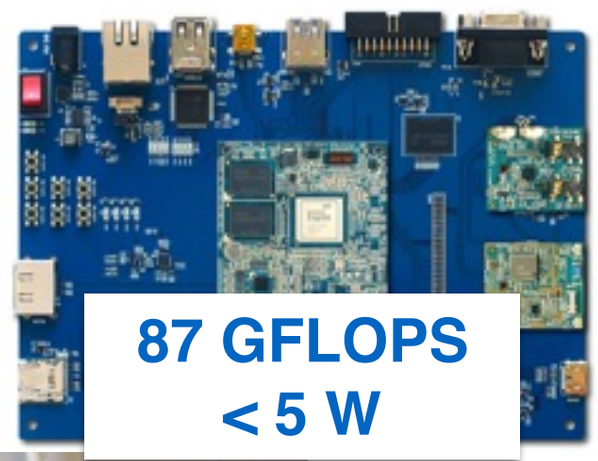
[Nardi et al., 2015]

Demo time

Machines	TITAN	GTX870M	TK1	ODROID	Arndale
CPU	Intel	Intel	ARM	ARM	ARM
CPU name	i7 Haswell	i7 Haswell	NVIDIA 4-Plus-1	Exynos 5422	Exynos 5250
CPU GFLOPS	448	307	74	80	27
CPU cores	4	4	4 + 1	4 + 4	2
GPU	NVIDIA	NVIDIA	NVIDIA	ARM	ARM
GPU name	TITAN	GTX 870M	Tegra K1	Mali-T628	Mali-T604
GPU GFLOPS	4500	2520	330	60 + 30	60

Platforms

[Nardi et al., 2015]



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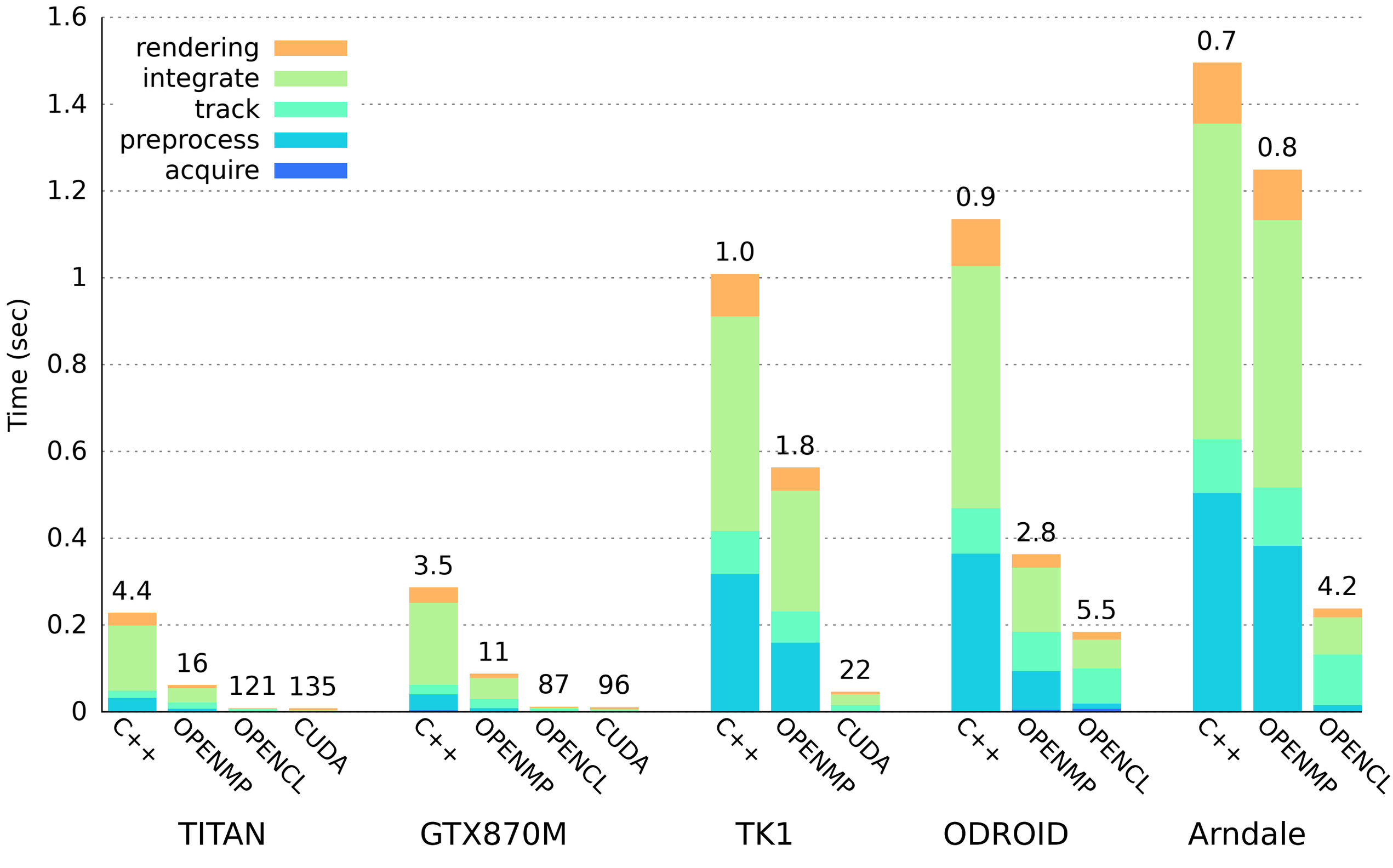
“Performance”: execution time

Mean time per frame (lower is better)



“Performance” on SLAMBench

- Runtime/energy/accuracy measurements
- Accuracy provided via absolute trajectory error (ATE)

Machine	CPU	CPU name	CPU GFLOPS	CPU cores	GPU	GPU name	GPU GFLOPS	TDP Watts
Hardkernel ODROID-XU3	ARM A15 + A7	Exynos 5422	80	4 + 4	ARM	Mali-T628	60 + 30	10

“Performance” on SLAMBench

- Runtime/energy/accuracy measurements
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ATE in cm	
C++	2.06
OpenMP	2.06
OpenCL	2.01

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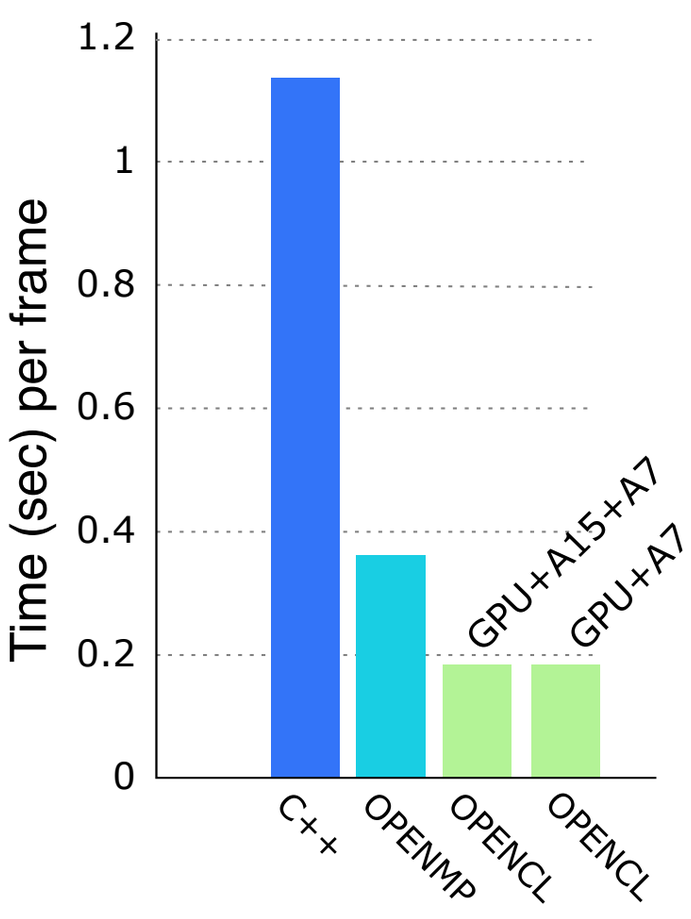
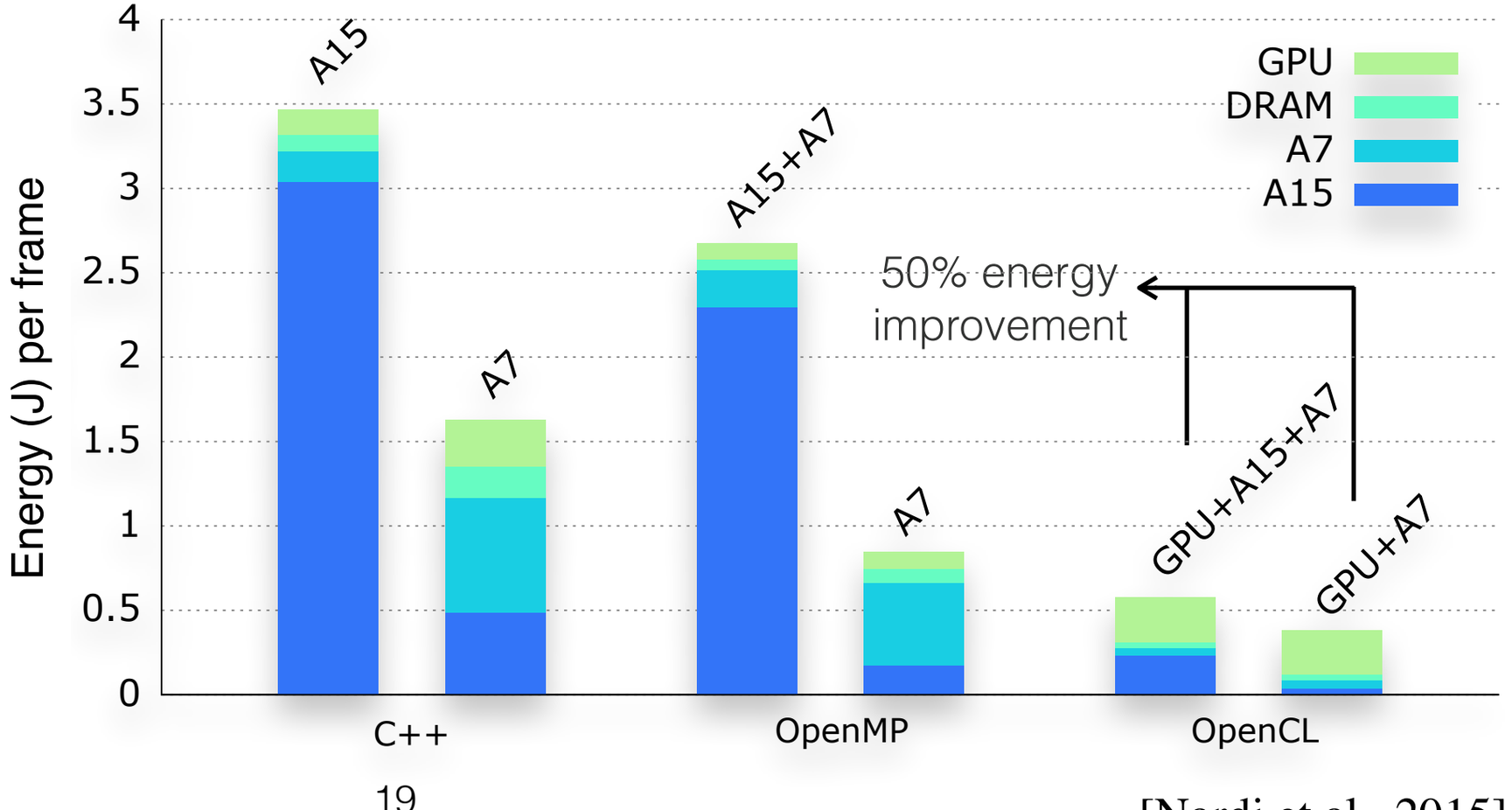
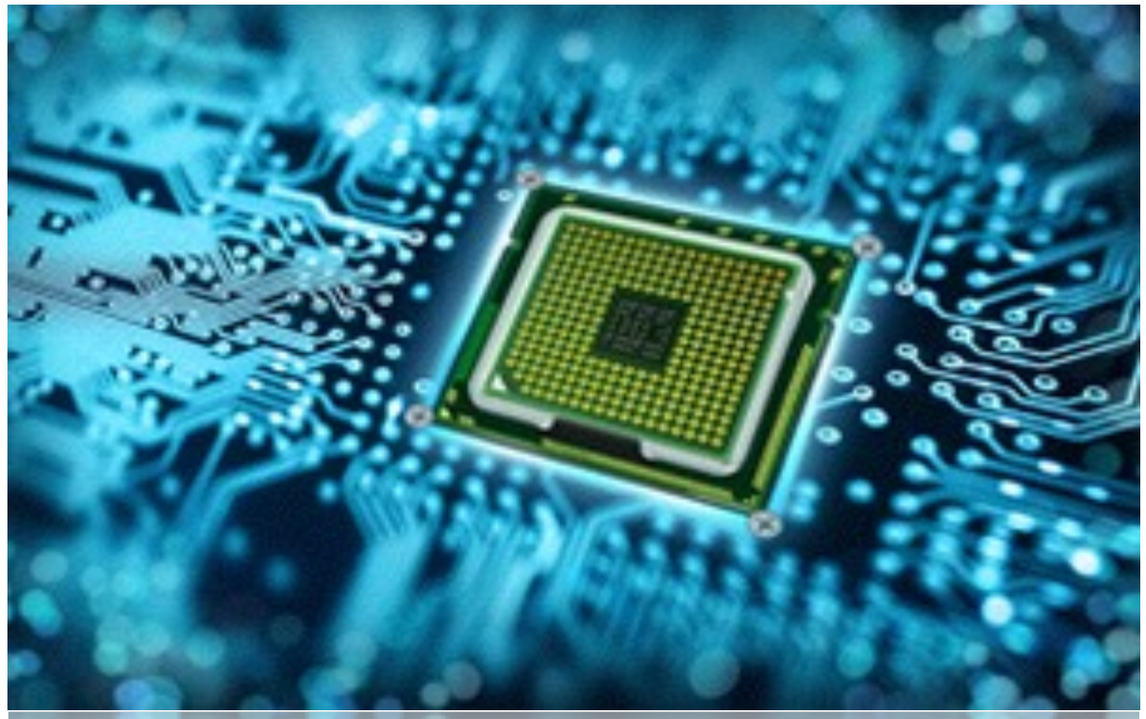




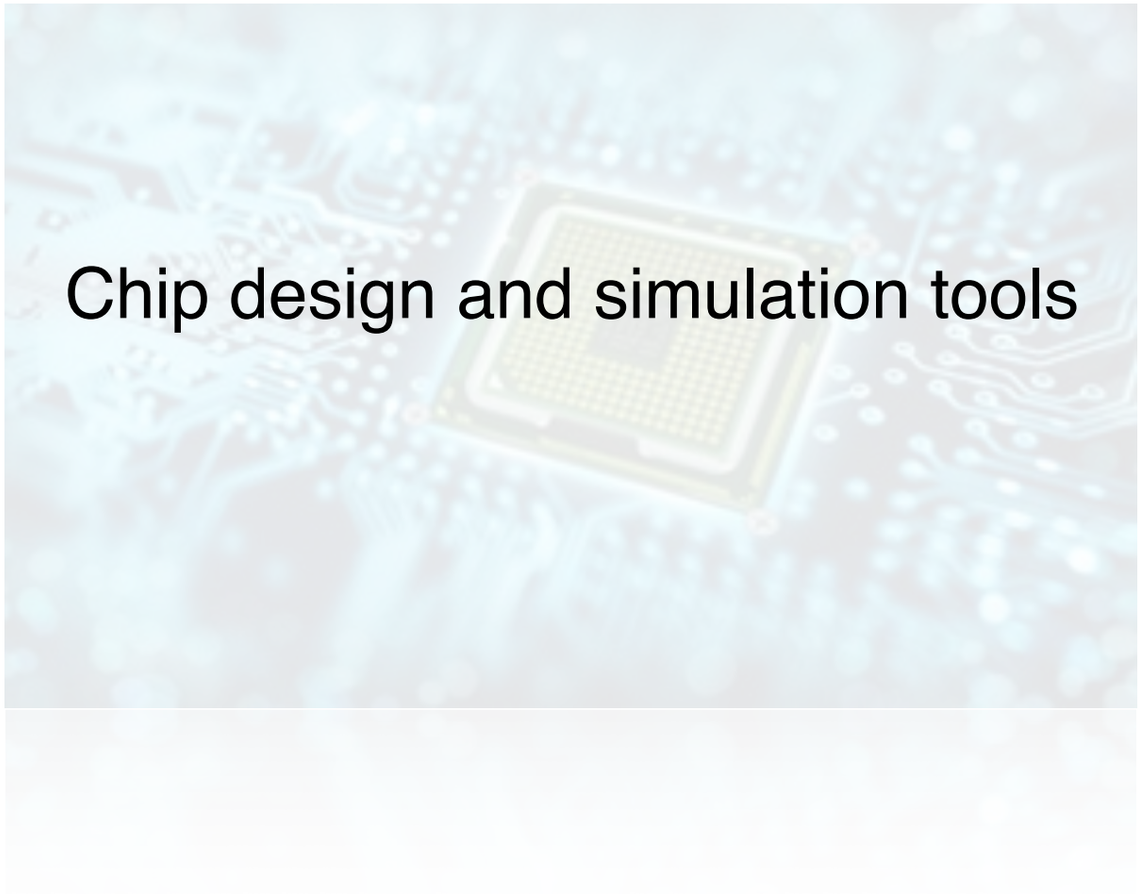
[Nardi et al., 2015]

SLAMBench opportunities



Chip design and simulation tools

SLAMBench opportunities



SLAMBench opportunities

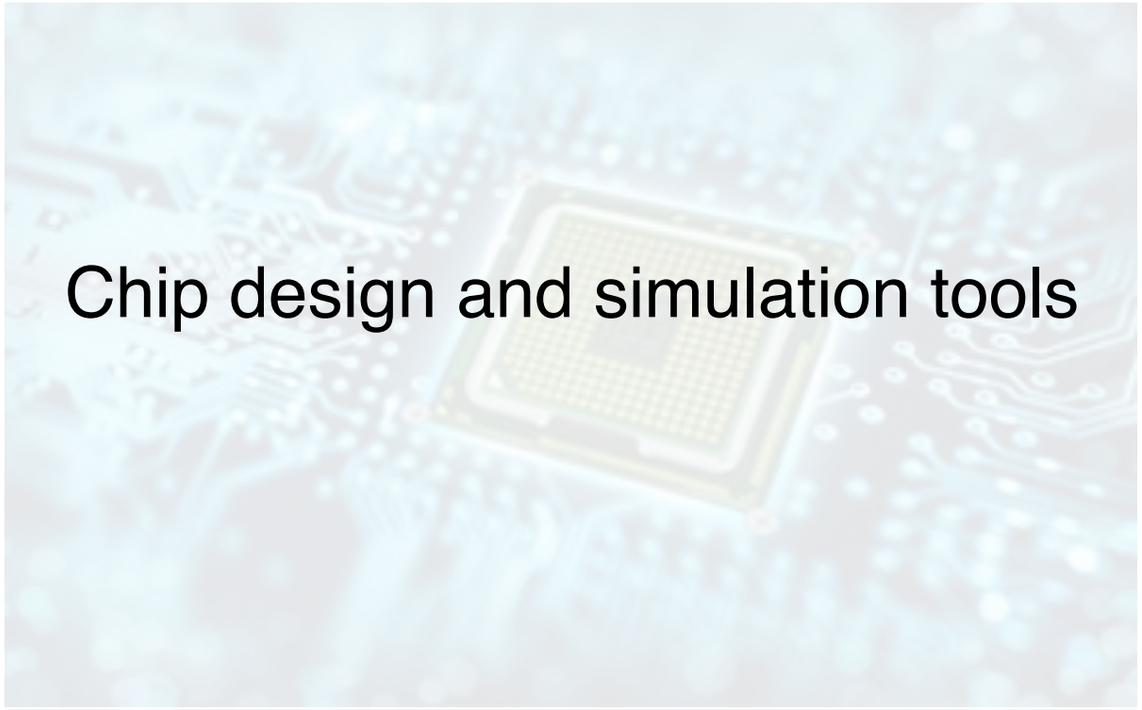
Chip design and simulation tools

SLAMBench evolution:

- Point fusion
- Octrees
- Semi-dense SLAM
- Feature-based SLAM

Kernels can be improved individually

SLAMBench opportunities



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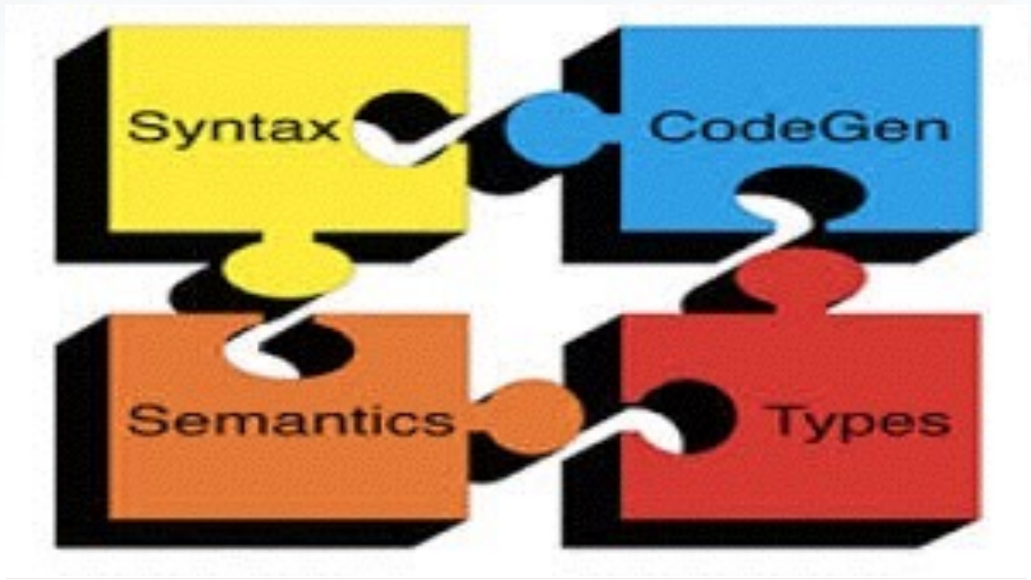

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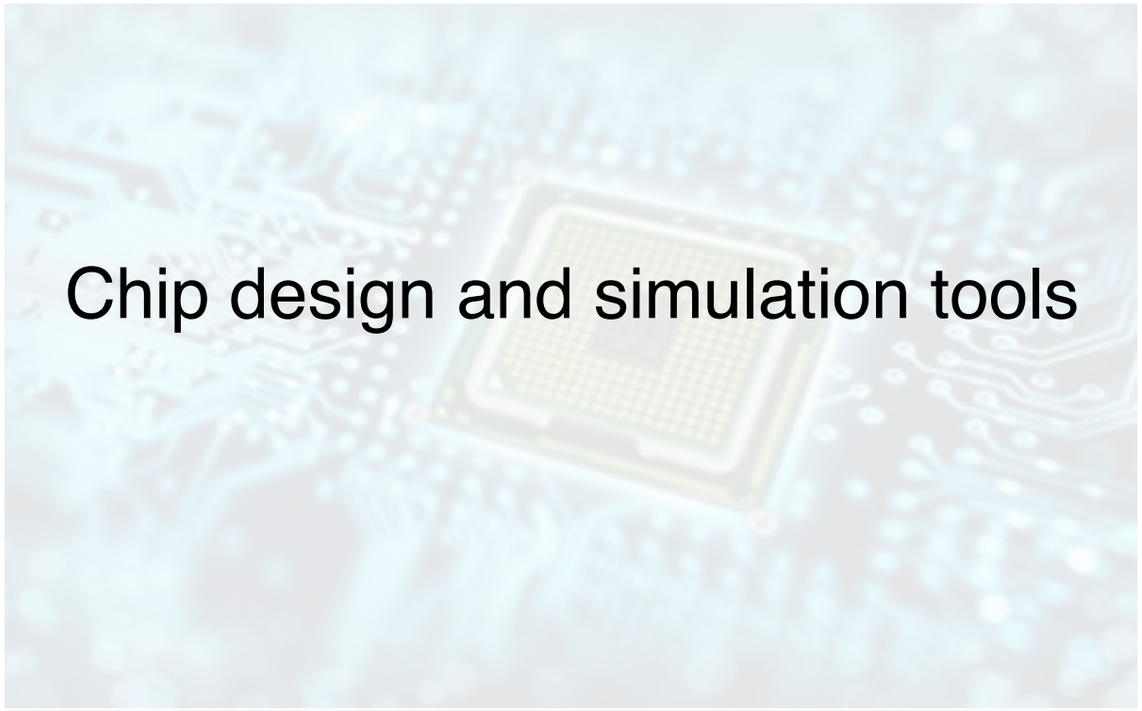
Kernels can be improved individually

Domain-specific language (DSL) targeting high performance, low-power solutions

Design-space exploration, e.g. algorithmic, compiler and hardware parameters

SLAMBench kernels tuning, e.g. vectorisation, GPU, auto-tuning

SLAMBench opportunities



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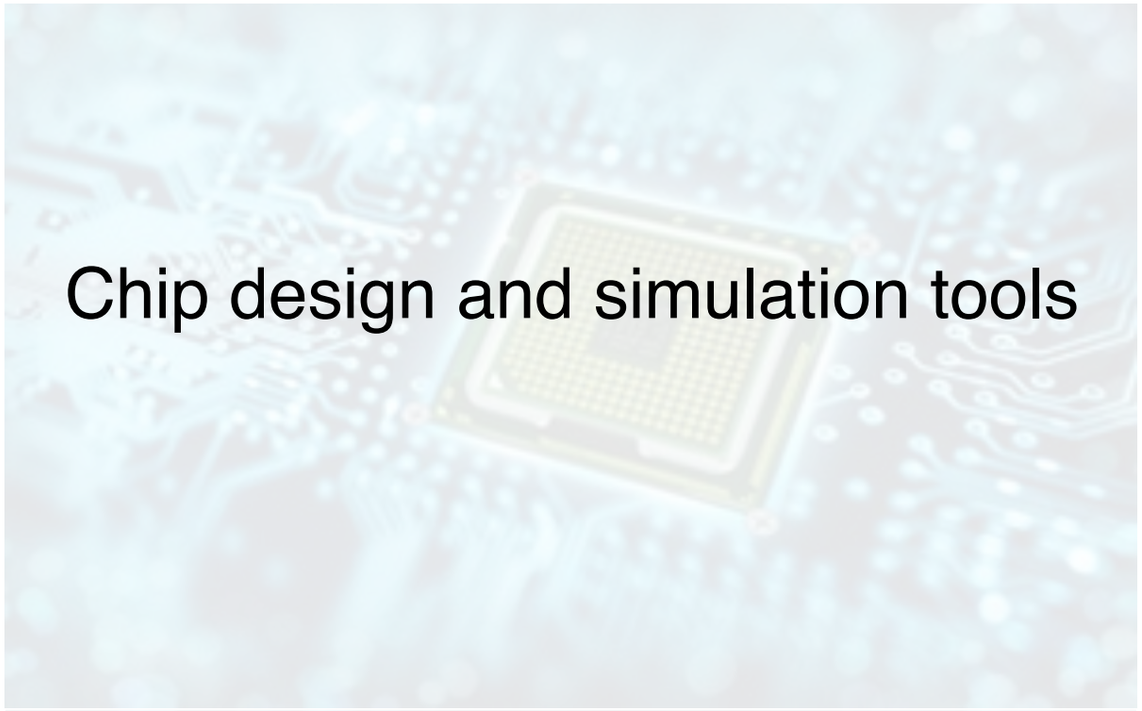

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Kernels can be improved individually

- CPU/GPU mapping/partitioning
- Just-in-time compilation

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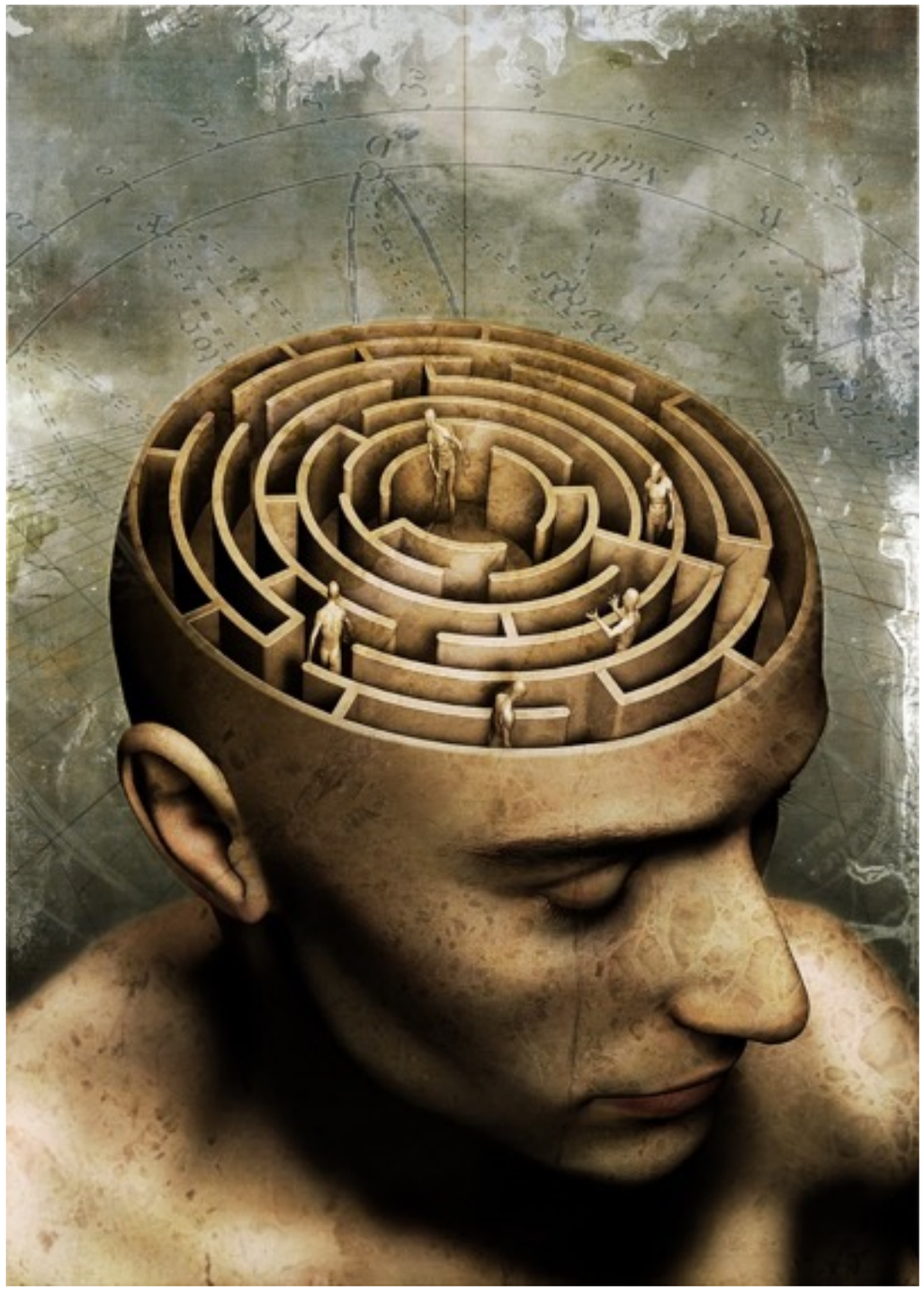

What is the optimisation space?

Configuration parameters:

Space 1

1. Algorithmic:
   - Application-specific parameters
   - Minimisation methods
   - Early exit condition values

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Space 2

2. Compilation:
   - opencl-params: -cl-mad-enable,-cl-fast-relaxed-math, etc.
   - LLVM flags: O1, O2, O3, vectorize-slp-aggressive, etc.
   - Local work group size: 16/32/64/96/112/128/256
   - Vectorisation: width (1/2/4/8), direction (x/y)
   - Thread coarsening: factor (1/2/4/8/16/32), stride (1/2/4/8/16/32), dimension (x/y)

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Space 3

3. Architecture:
   - GPU frequency: 177/266/350/420/480/543/600/DVFS
   - # of active big cores: 0/1/2/3/4
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Warning: huge spaces, impossible to run exhaustively

KinectFusion algorithmic features

Features	Ranges
Volume resolution	64x64x64, 128x128x128, 256x256x256, 512x512x512
μ distance	0 .. 0.5
Pyramid level iterations (3 levels)	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
Image resolution (image ratio)	1, 2, 4, 8
Tracking rate	1, 2, 3, 4, 5
ICP threshold	10^{-6} .. 10^{2}
Integration rate	1 .. 30

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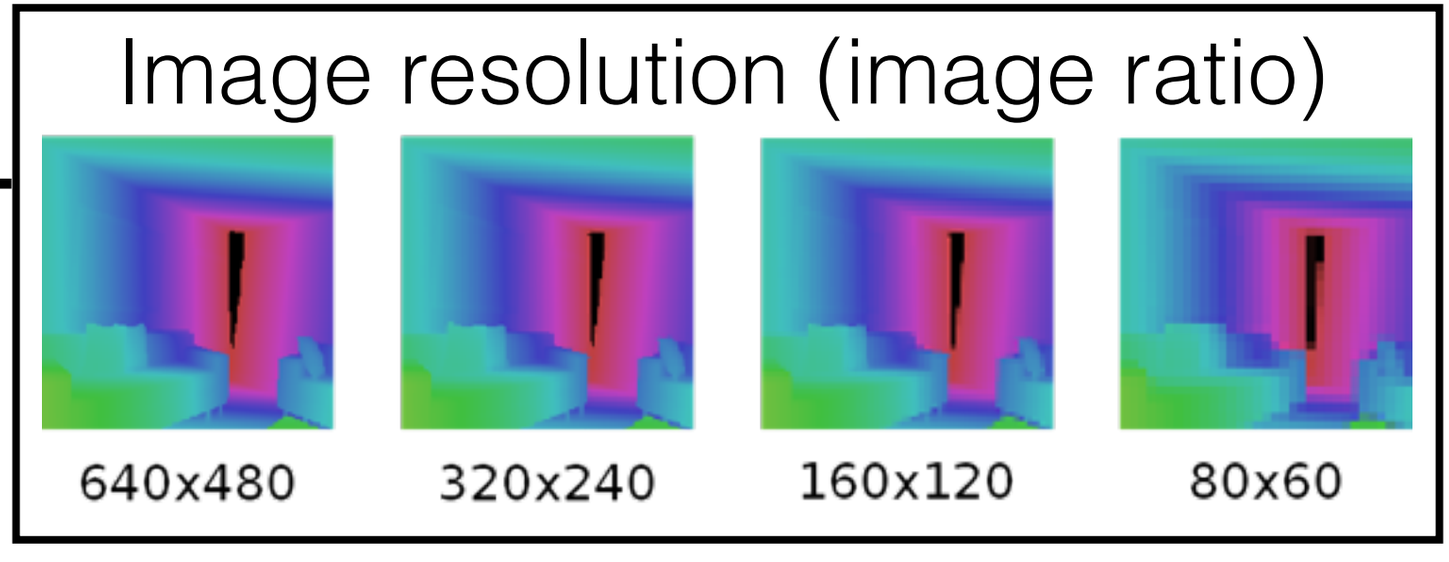

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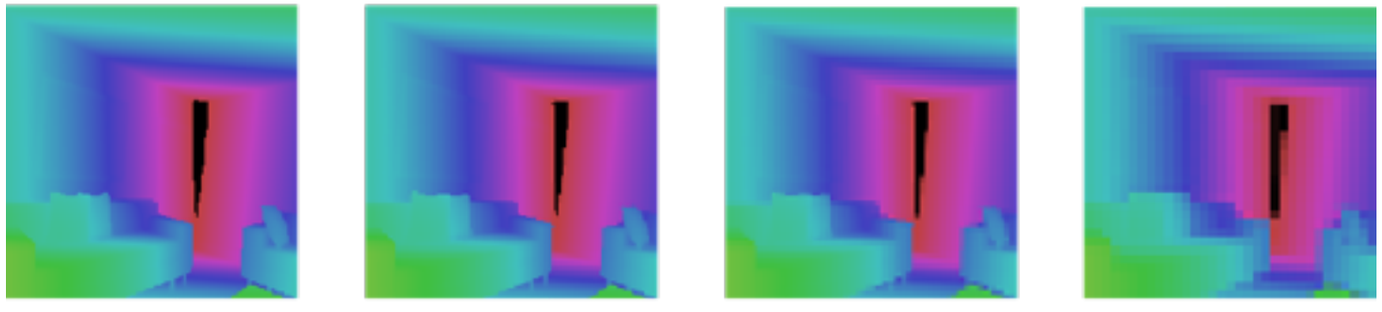
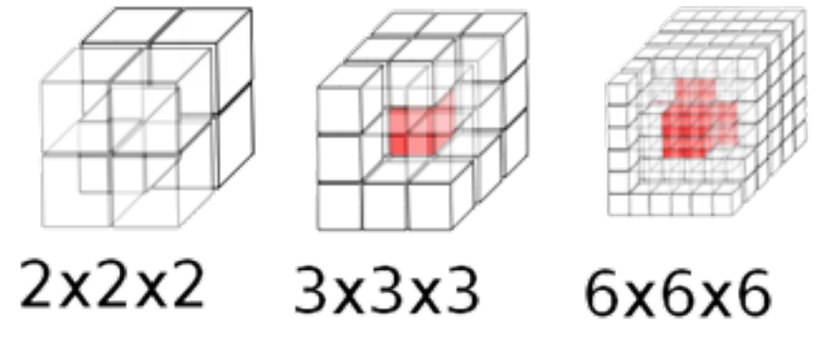
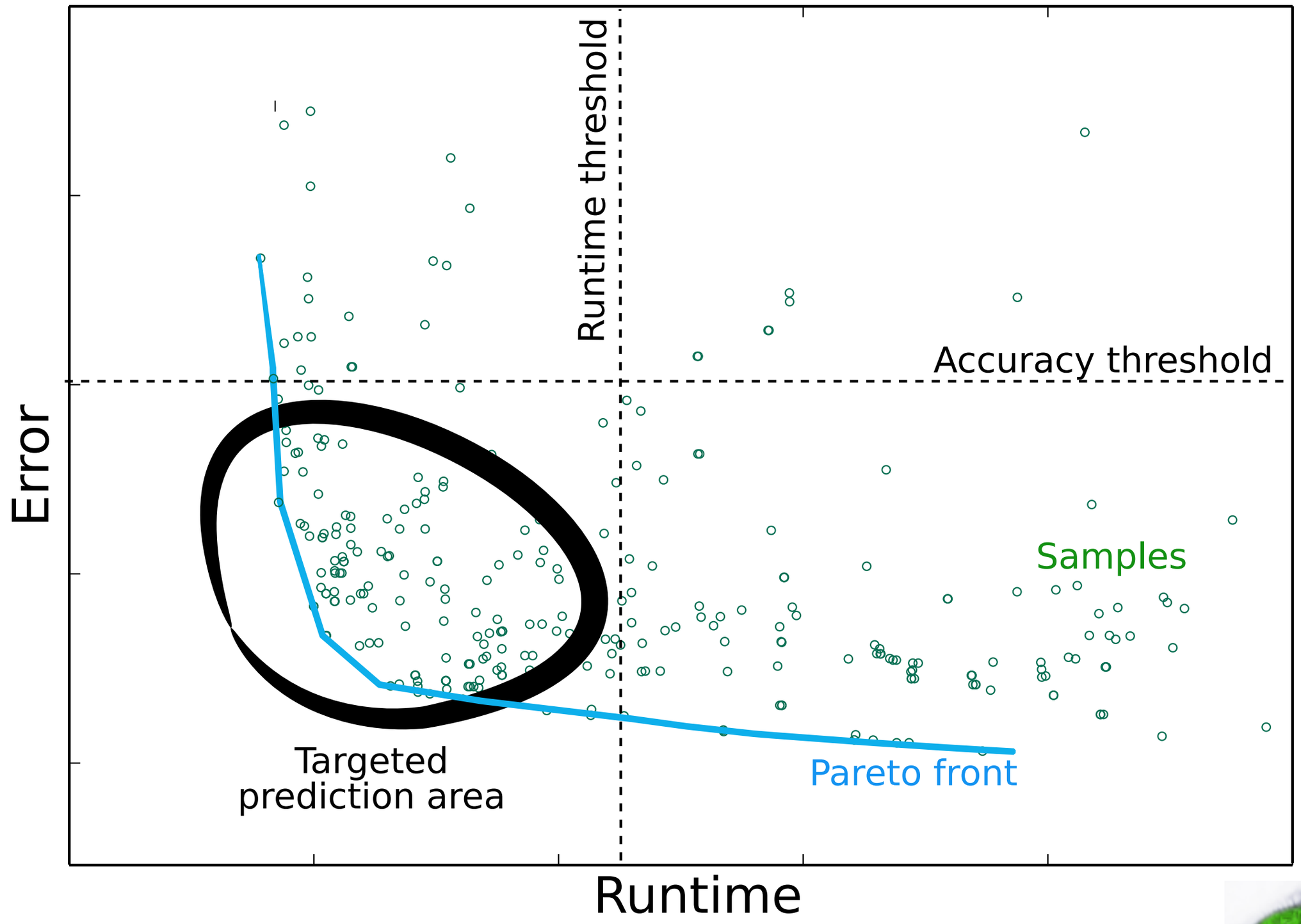
Image resolution (image ratio)



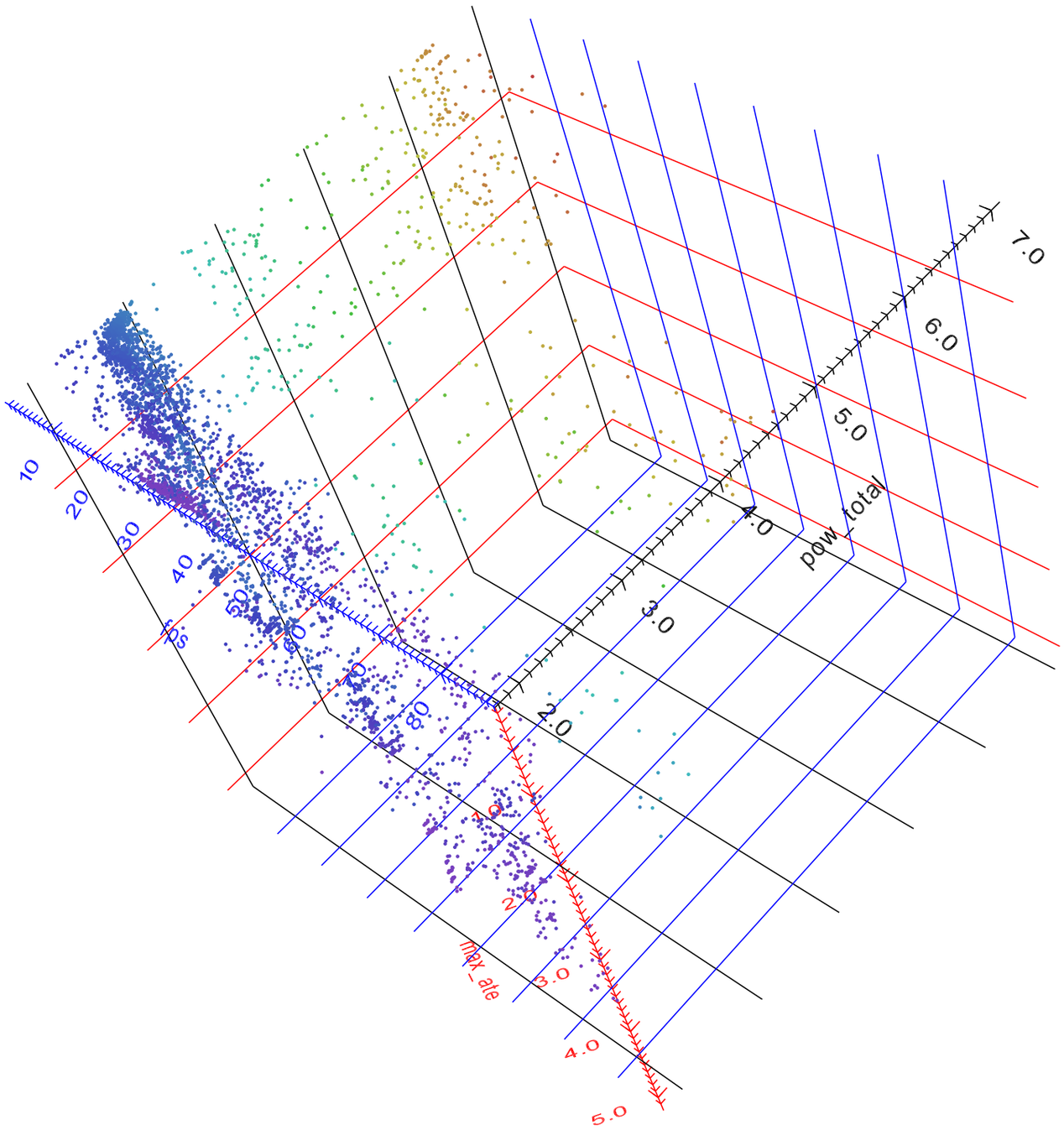
Volume resolution



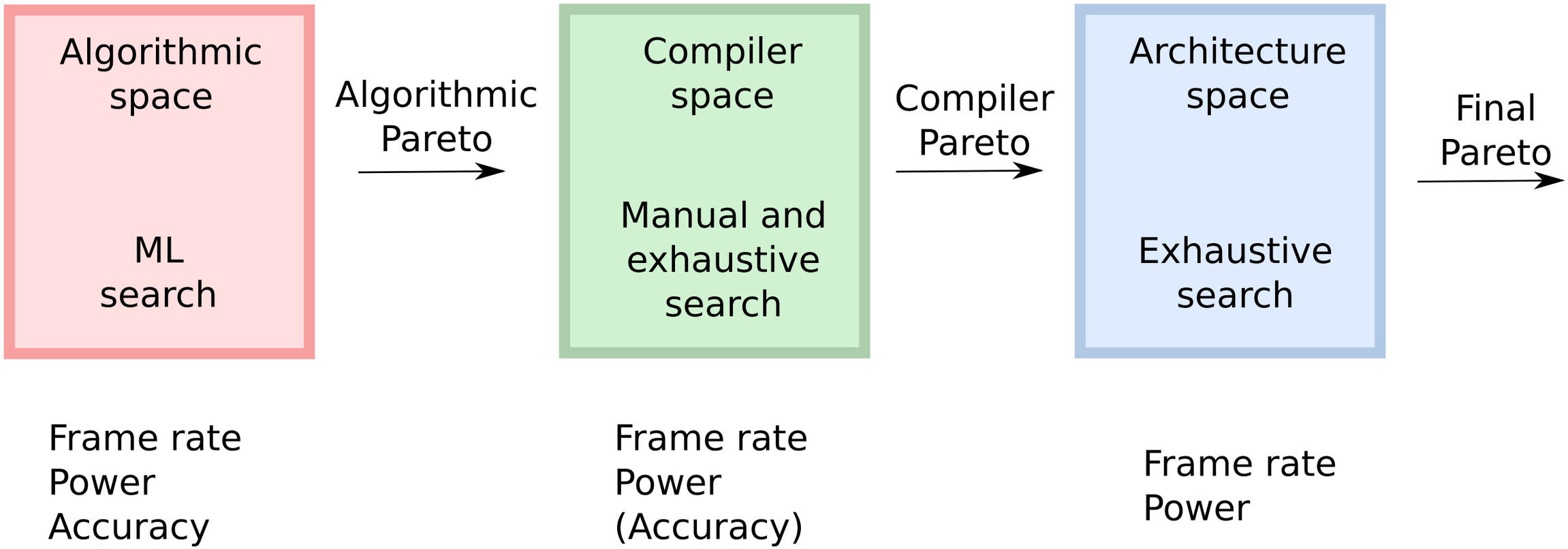
Exploration goal



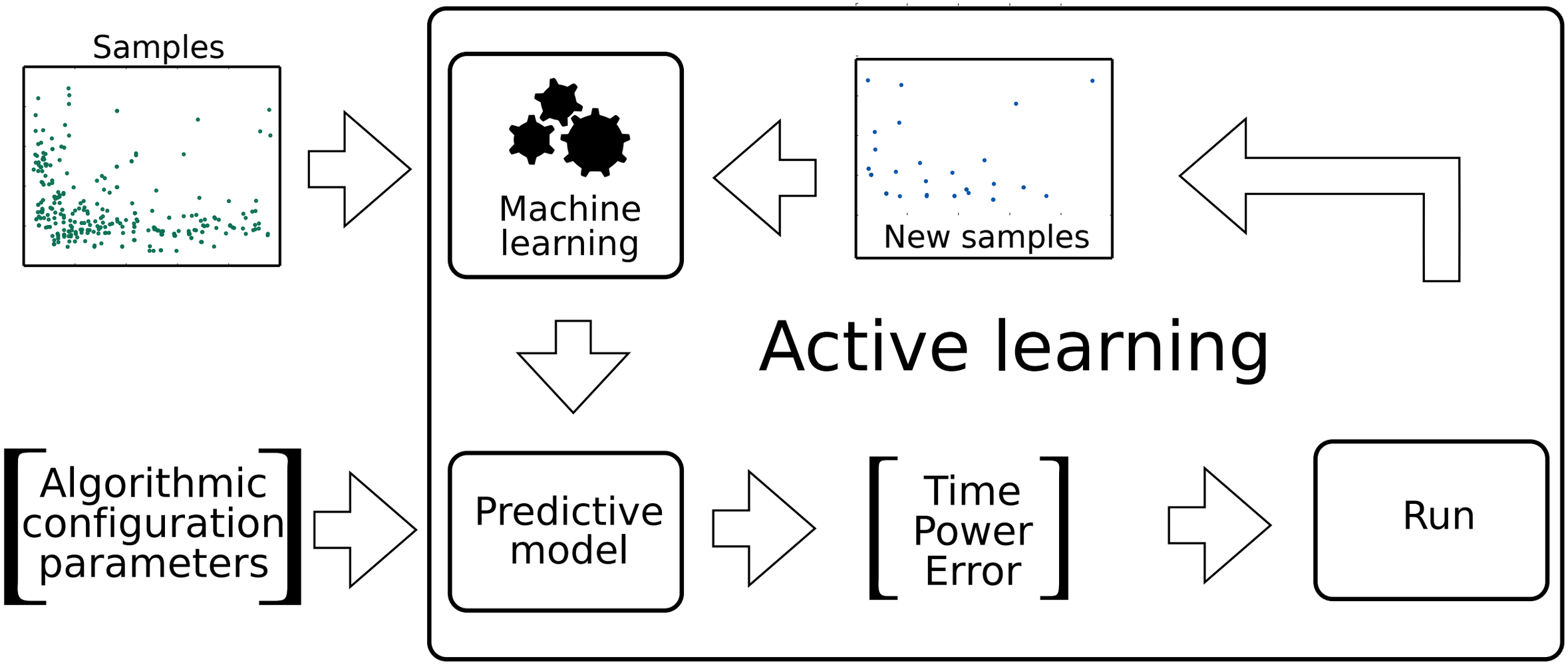
Three-objective optimisation goal



Incremental exploration approach

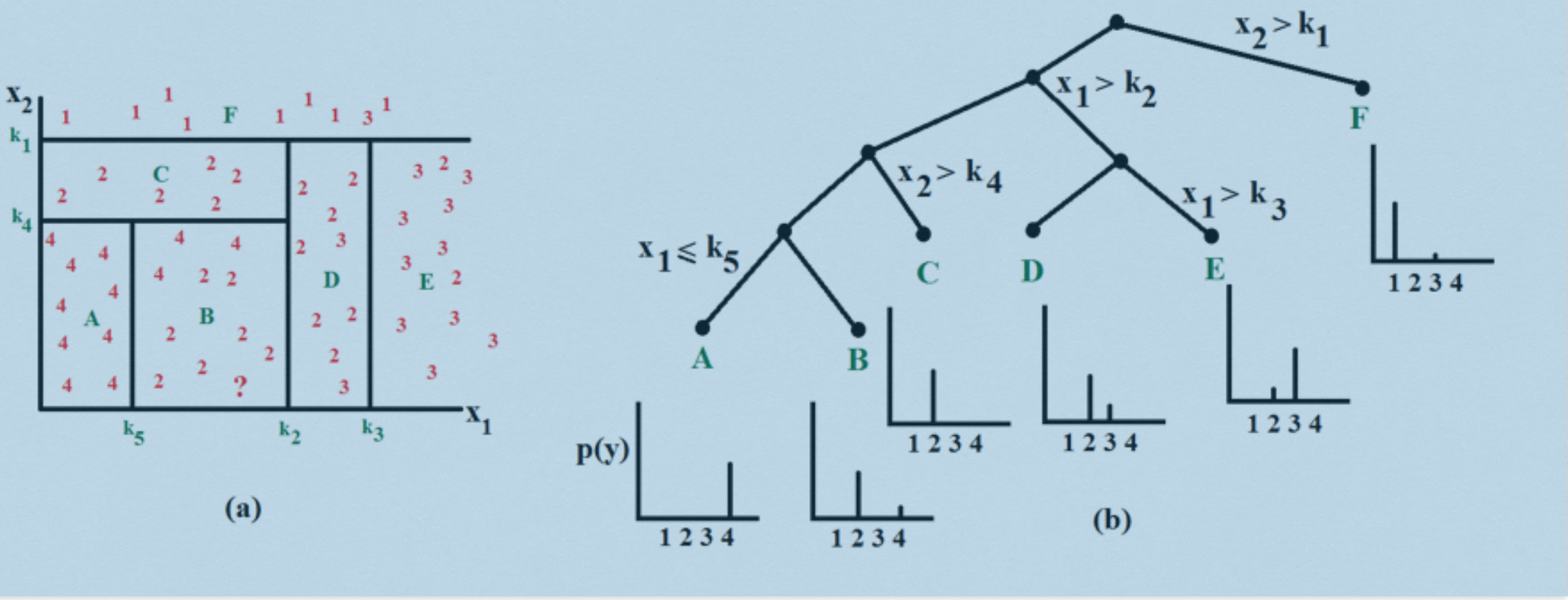


Algo design-space exploration (DSE)

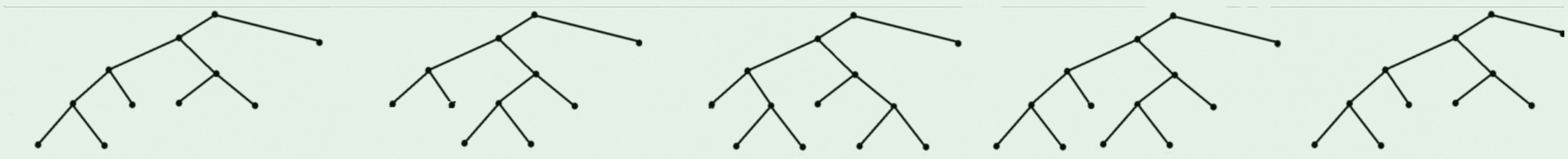


Machine learning methods used

Decision tree



Random forest



DSE on algorithmic parameters error/runtime

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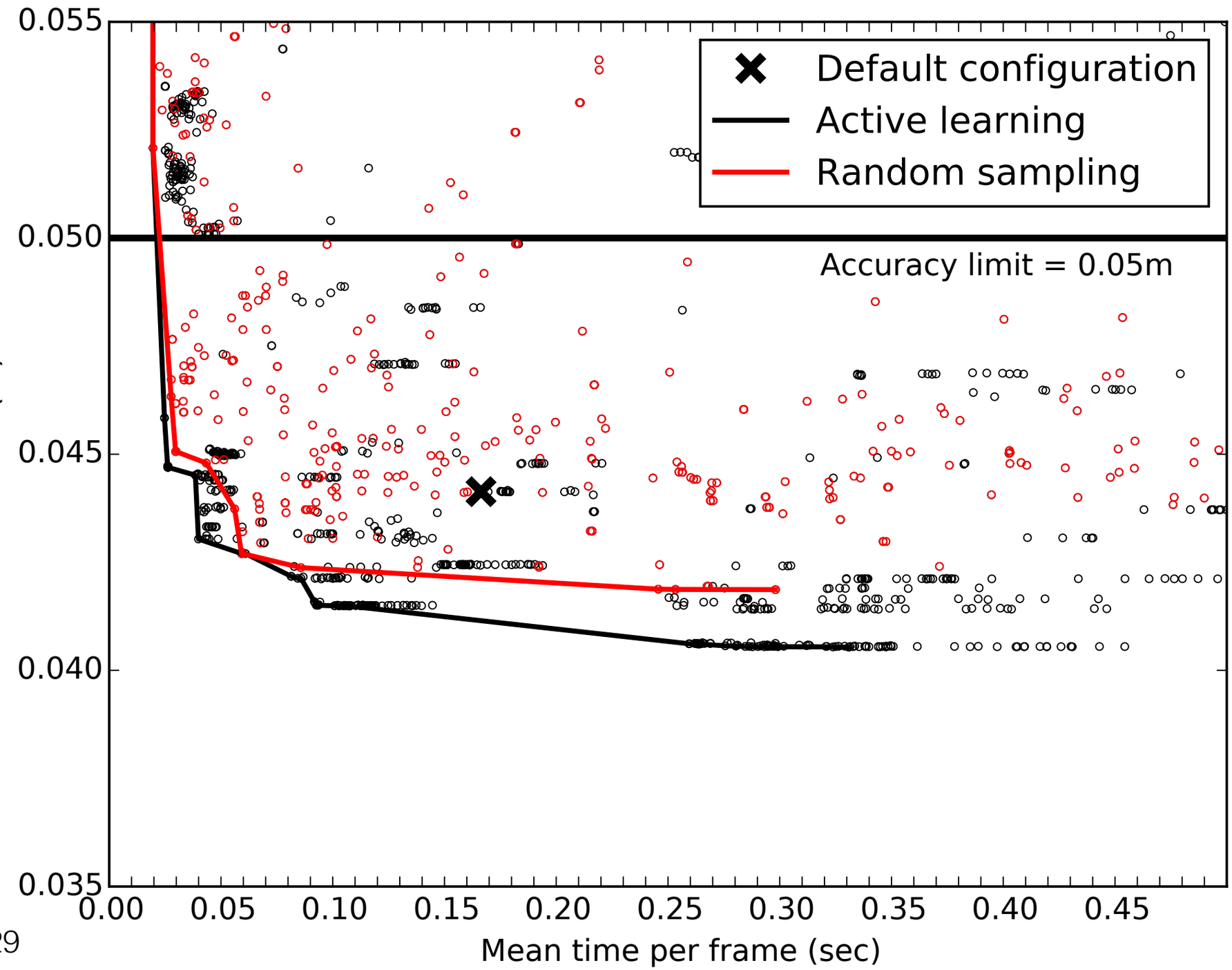
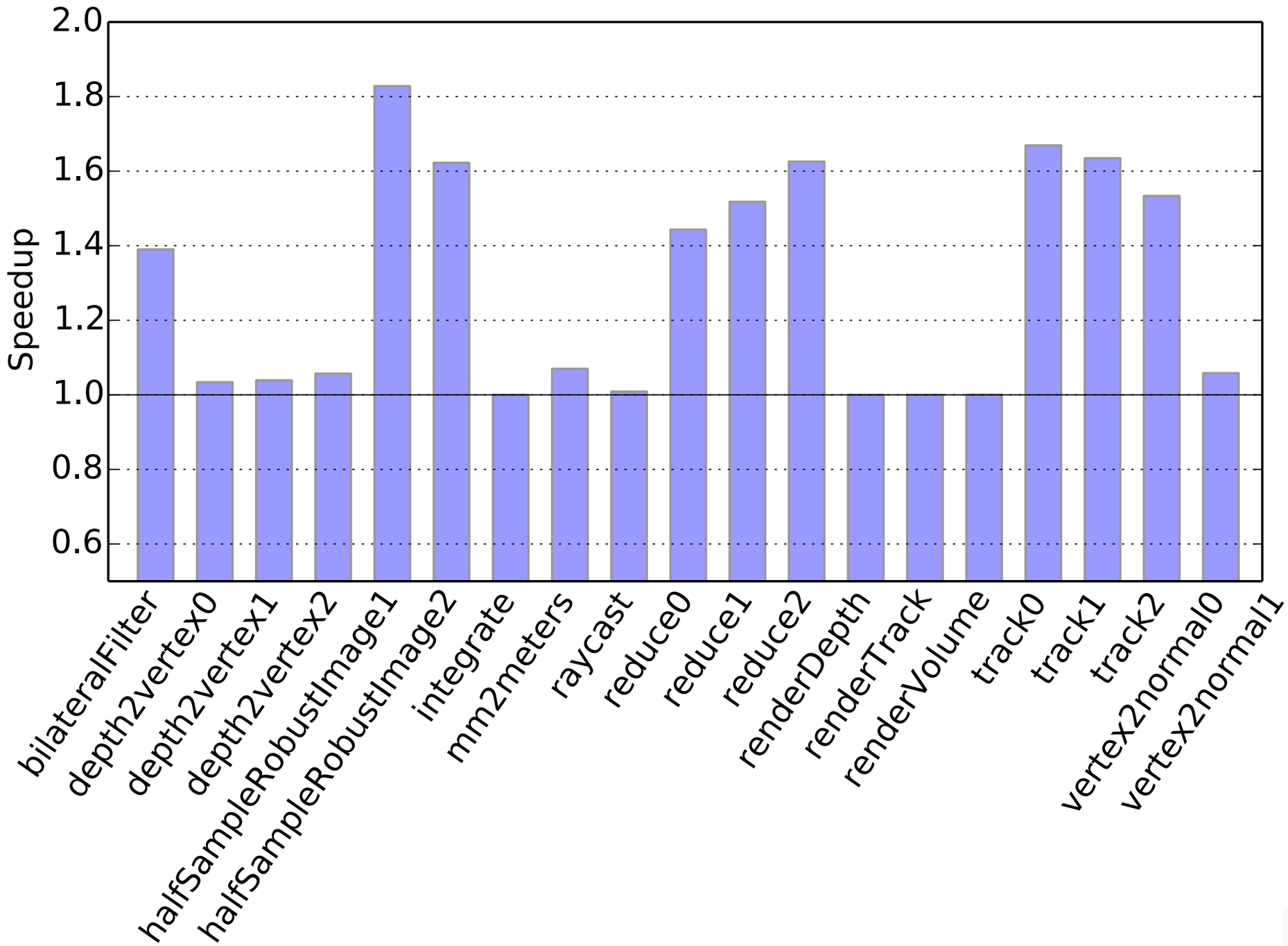
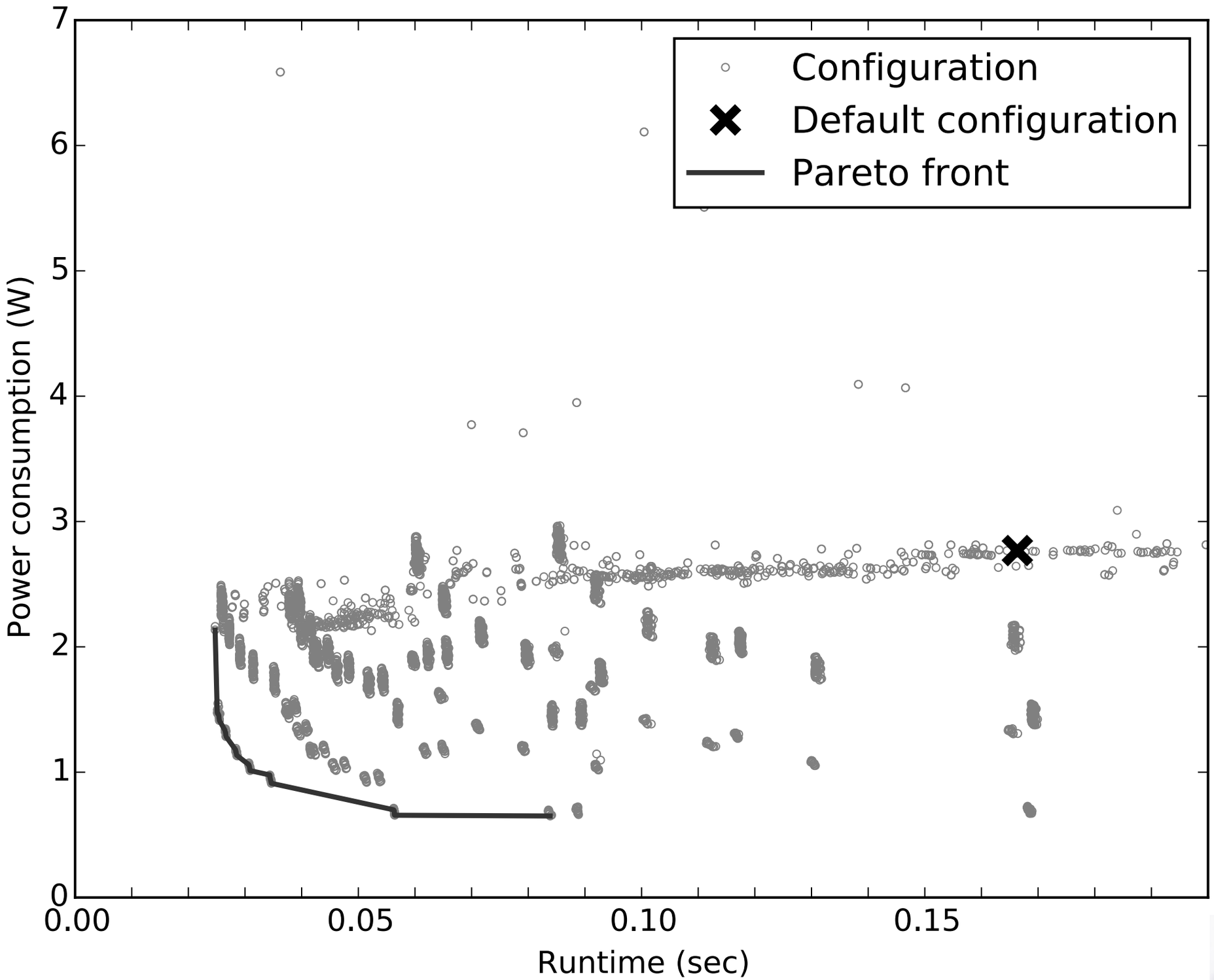
Hardkernel **ODROID-XU3**	ARM A15 + A7	Exynos 5422	80	4 + 4	ARM	Mali-T628	60 + 30	10



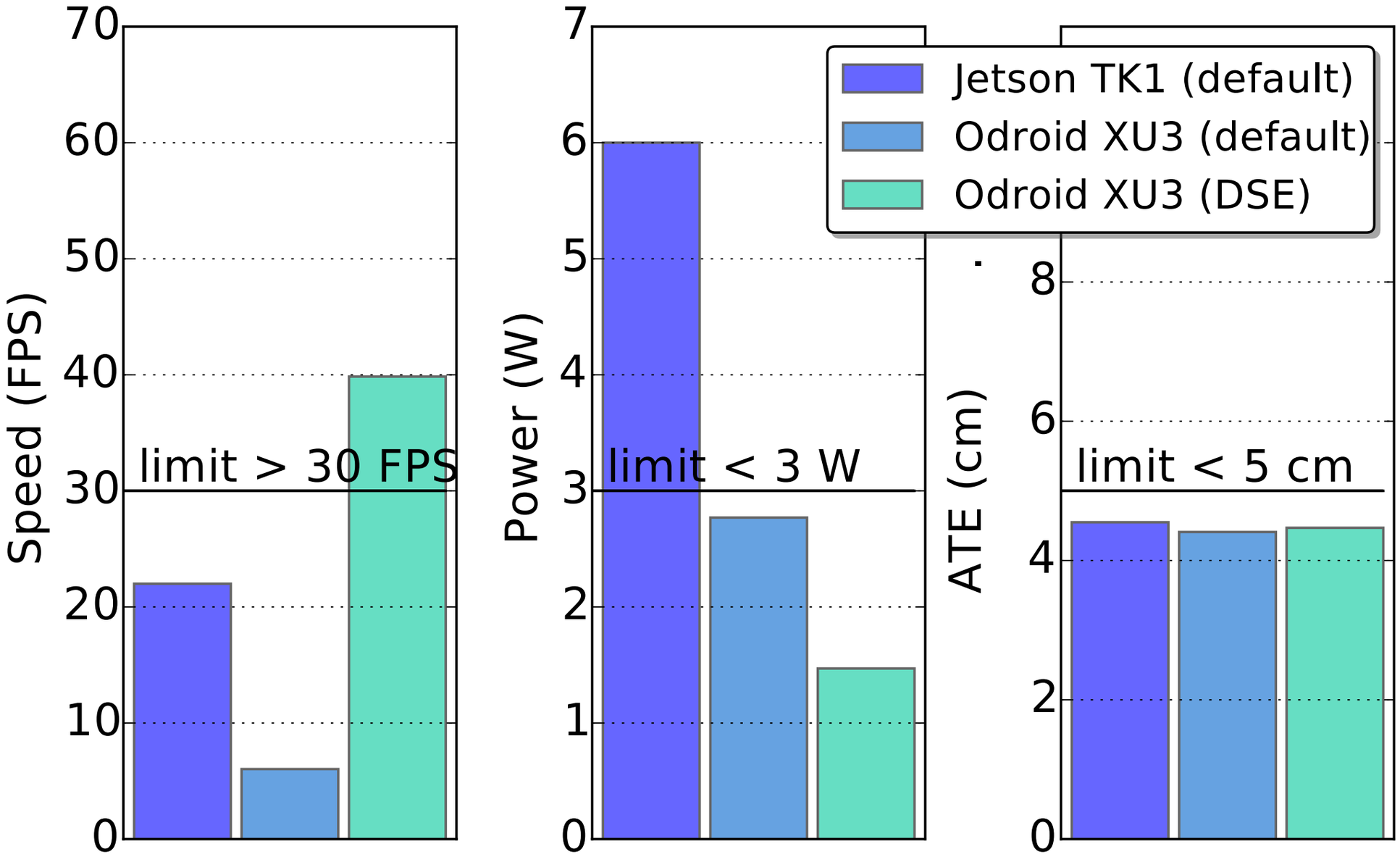
DSE compiler parameters speedup



DSE architecture parameters power/runtime



DSE final result I



Integrating algorithmic parameters into benchmarking and design space exploration in dense 3D scene understanding (PACT 2016)

DSE final result II

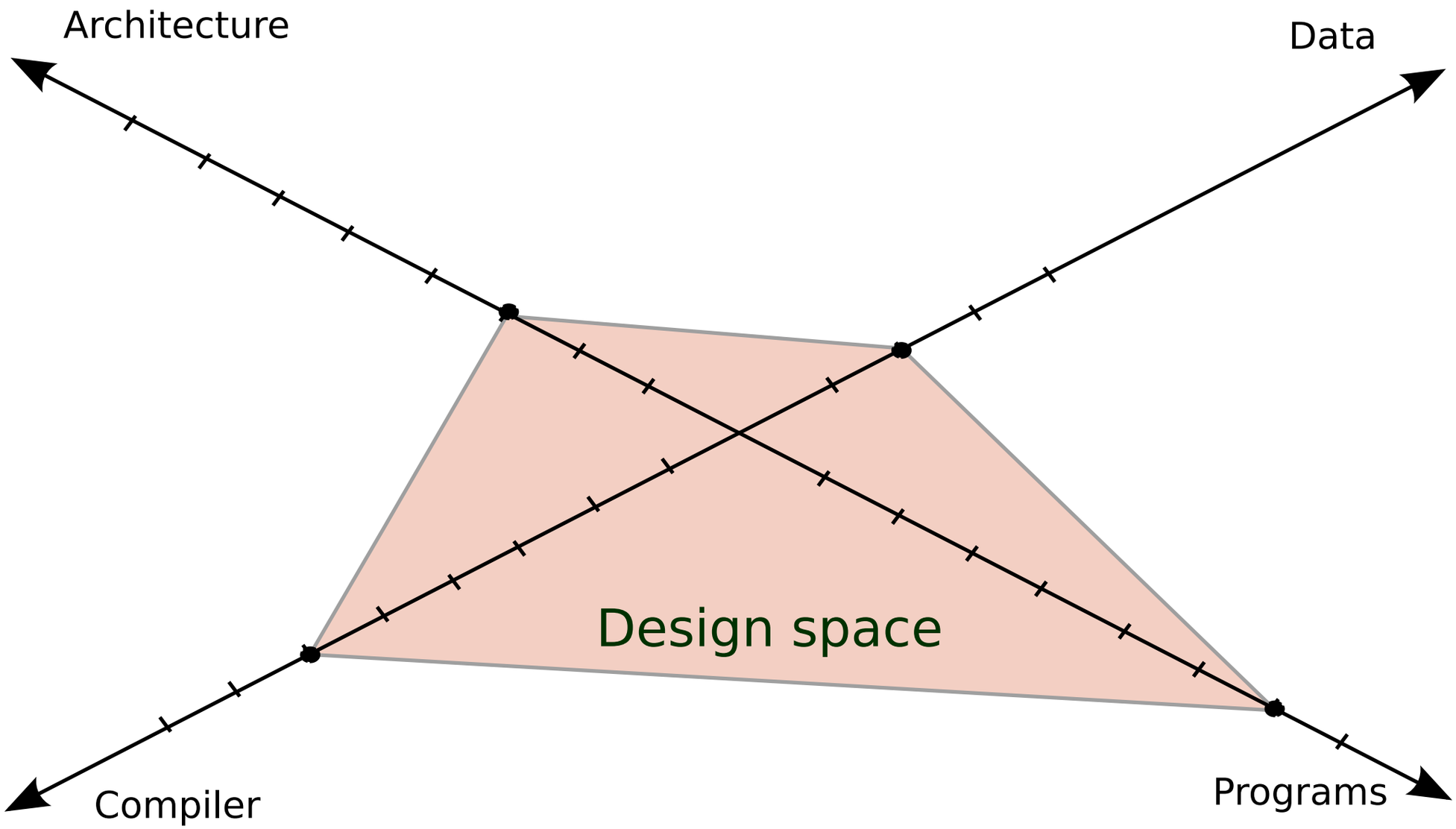
Constraint	Runtime (FPS)	Max ATE (cm)	Power (Watts)
Default	6.03	4.41	2.77
Best runtime	39.85	4.47	1.47
Best accuracy	1.51	3.30	2.38
Best power	11.92	4.45	0.65
Power $<$ 1W	29.09	4.47	0.98
Power $<$ 2W	39.85	4.47	1.47
FPS $>$ 10	11.92	4.45	0.65
FPS $>$ 20	28.87	4.47	0.91
FPS $>$ 30	32.38	4.47	1.01

- Most of the improvement comes from the algorithmic space
- KinectFusion real-time on a popular embedded device
- Enabling auto-tuning at the domain-specific language (DSL) level

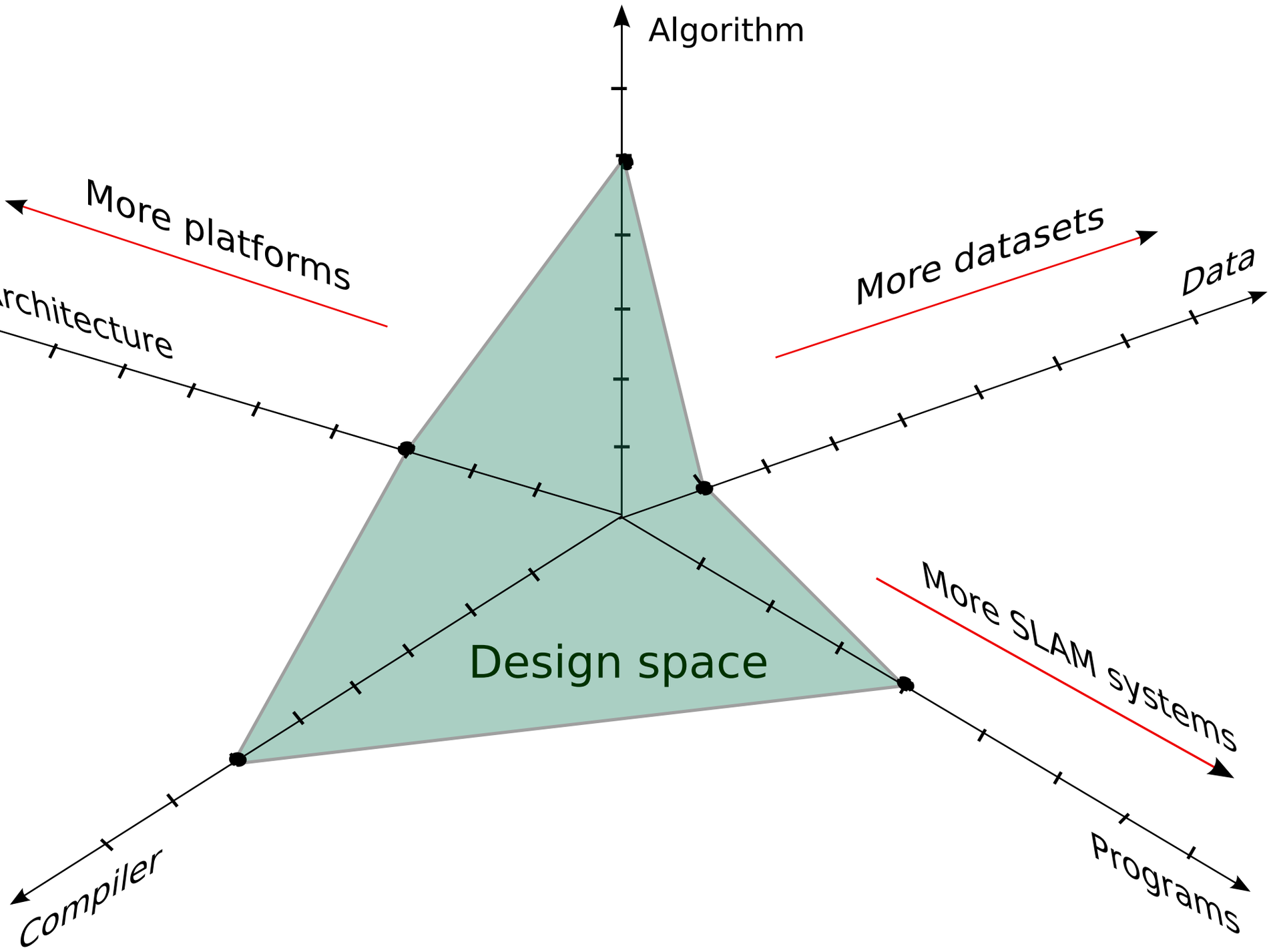
SLAMBench vs other benchmarking frameworks

- Multi-objective optimisation: frame rate/power/accuracy
- Semantic accuracy check is very powerful:
  - enables non bit-wise accuracy check
  - scope for aggressive approx. computing and auto-tuning
- Several datasets:
  - not just 1 "big" and 1 "small"
- Multi-kernel benchmark:
  - enables benchmarking complex frameworks
- Multiple applications from the same domain (SLAM)
  - this is coming …

DSE the big picture I



DSE the big picture II



SLAMBench today

- Publicly released 13/11/2014 (1300+ downloads)
- Early adopters:
  - Computer Vision
  - Compiler/runtime
  - Architecture

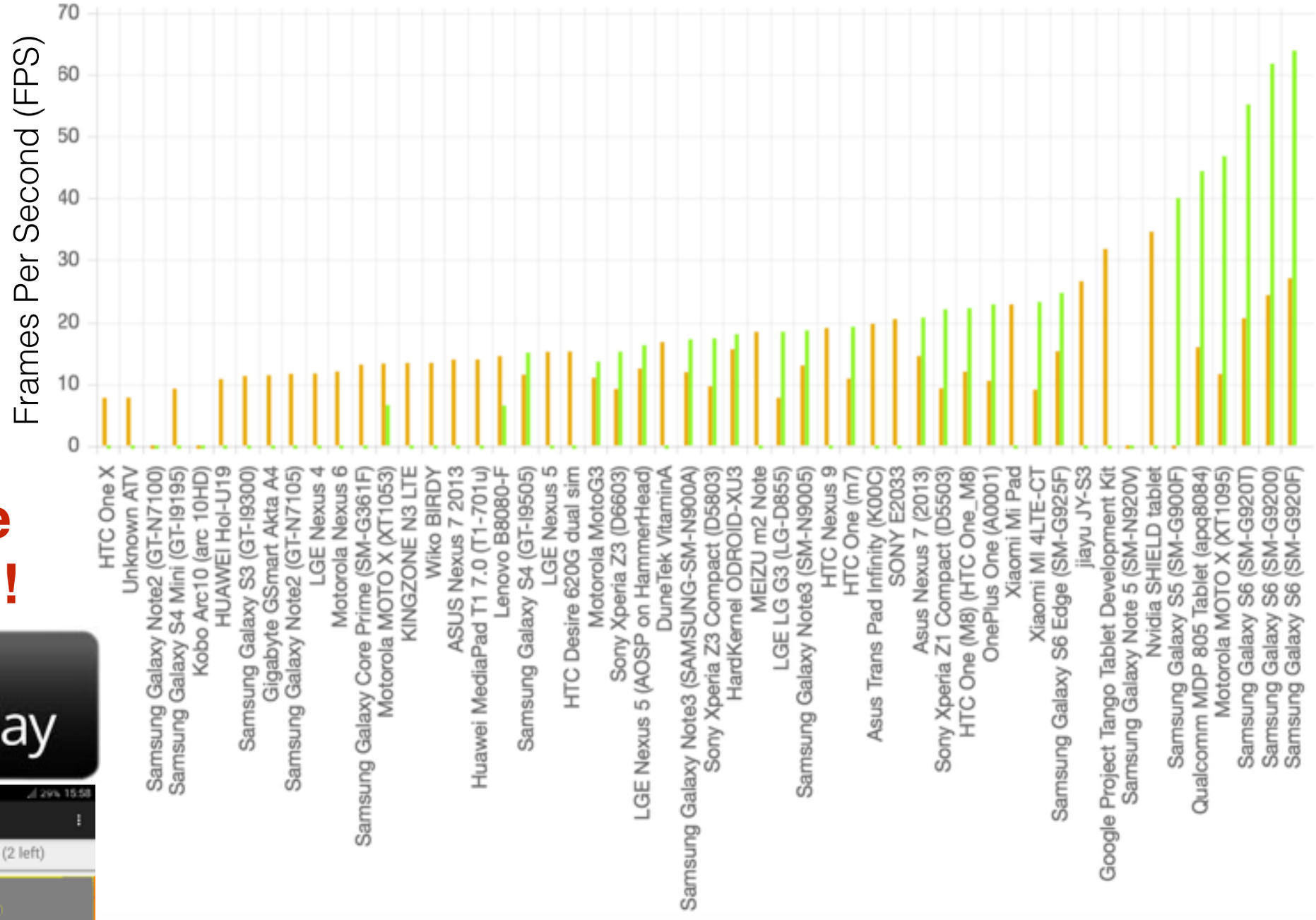
Papers for further reads

Web: apt.cs.manchester.ac.uk/projects/PAMELA/tools/SLAMBench/

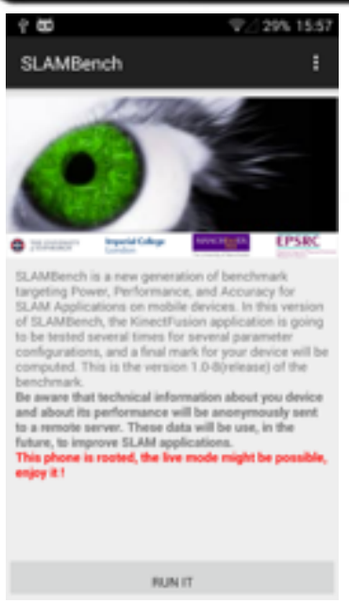
1. *Introducing SLAMBench, a performance and accuracy benchmarking methodology for SLAM (ICRA 2015)*
2. *Comparative Design Space Exploration of Dense and Semi-Dense SLAM (ICRA 2016)*
3. *Integrating algorithmic parameters into benchmarking and design space exploration in dense 3D scene understanding (PACT 2016)*
4. *Diplomat: mapping of multi-kernel applications using a static dataflow abstraction (MASCOTS 2016)*

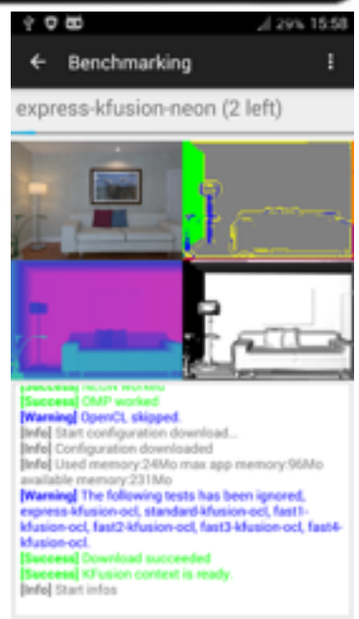
Crowdsourcing mobile Android SLAMBench

- SLAMBench OpenMP
- SLAMBench OpenCL



Get it now, And see where your device is!!





- It runs a set of configurations on the available languages on your device
- Then shows the best achieved result

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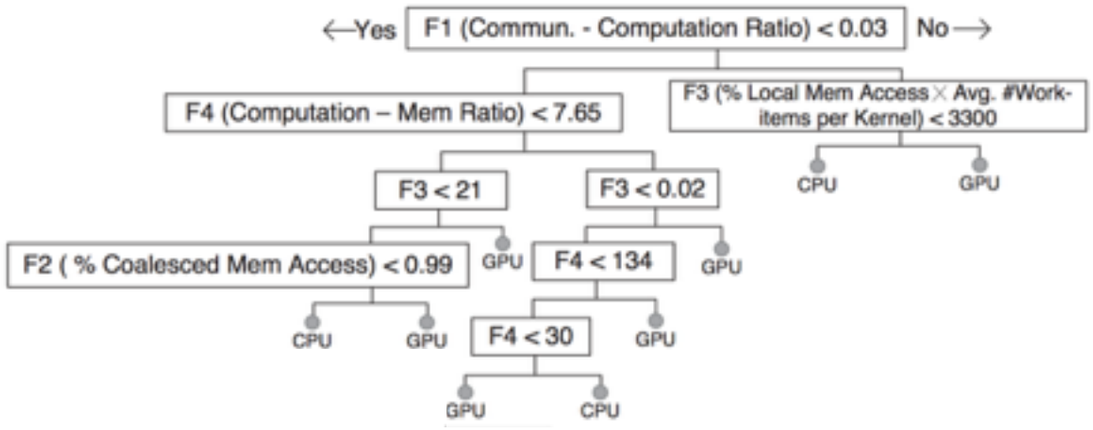
Backup slides

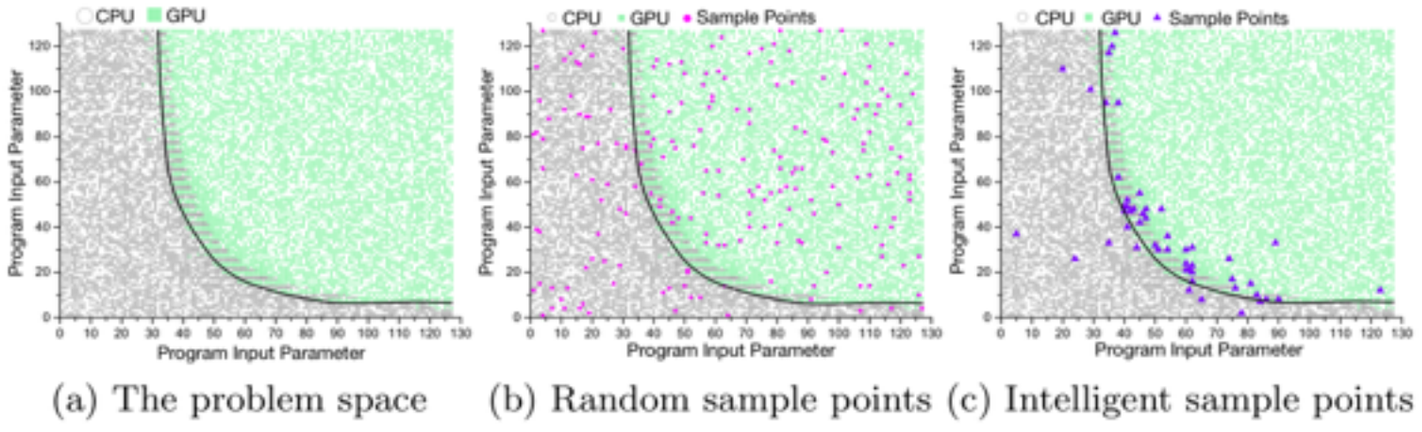
Why the DSE work is unique?

Luigi Nardi - Imperial College London

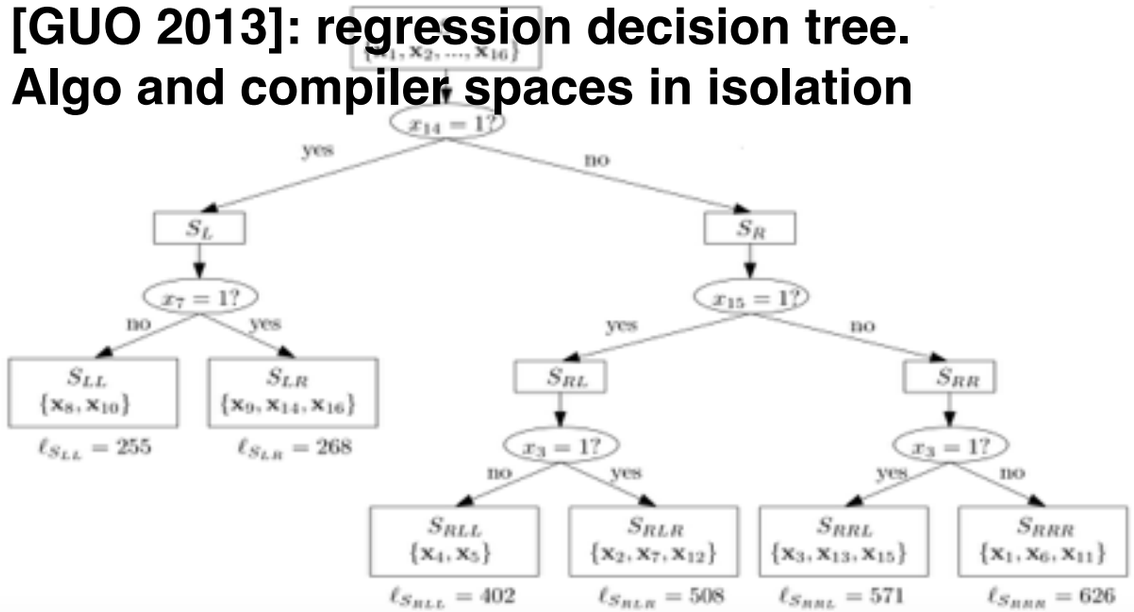
[Grewe 2011]: CPU/GPU mapping using a classification decision tree on code features



[Ogilvie 2014]: CPU/GPU static mapping using active learning and query by committee classifiers



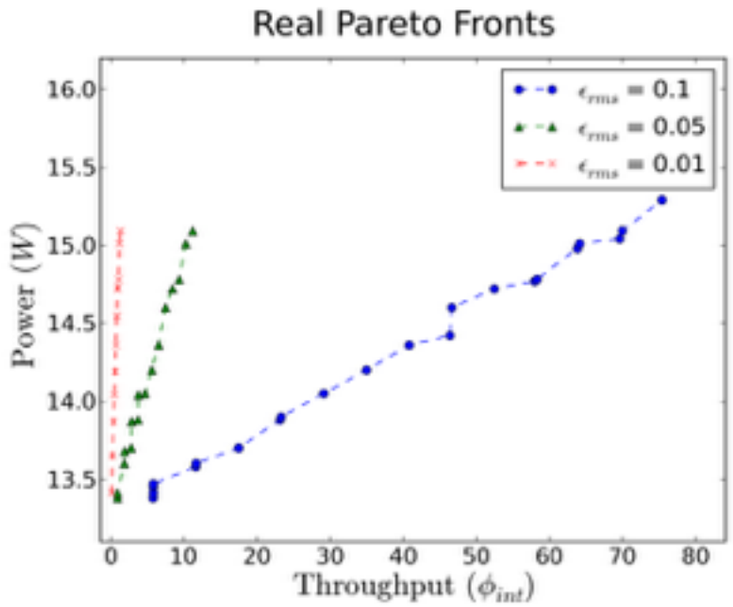
[GUO 2013]: regression decision tree. Algo and compiler spaces in isolation



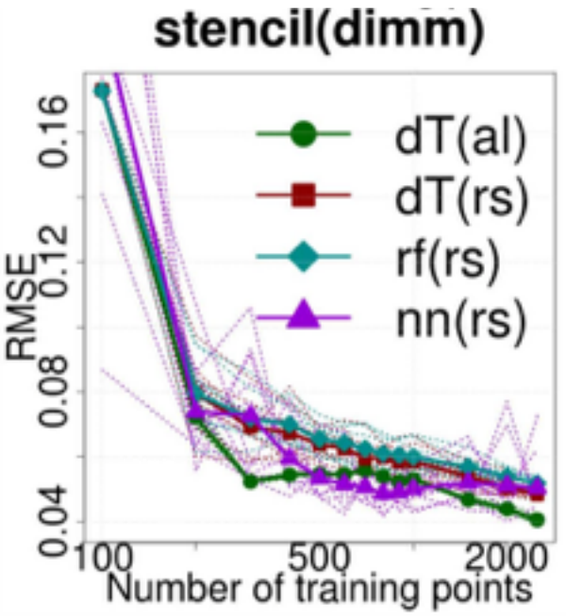
[Siegmund 2015]: performance-influence models using linear regression. Algo and compiler spaces in isolation

$$\Pi(c) = 50 + \overbrace{20{\cdot}c(E)}^{\phi_E} + \overbrace{15{\cdot}c(C)}^{\phi_C} + \overbrace{5{\cdot}c(S)}^{\phi_S} - \overbrace{0.5{\cdot}c(P)}^{\phi_P} + \overbrace{1.5{\cdot}c(D)^2}^{\phi_D} - \underbrace{10{\cdot}c(E){\cdot}c(C)}_{\Phi_{E,C}} + \underbrace{0.3{\cdot}c(E){\cdot}c(P)}_{\Phi_{E,P}} + \underbrace{2.5{\cdot}c(E){\cdot}c(C){\cdot}c(D)}_{\Phi_{E,C,D}}$$

[Kurek 2013]: MOMLO GPs, SVM, PSO. Joint algo and HW spaces



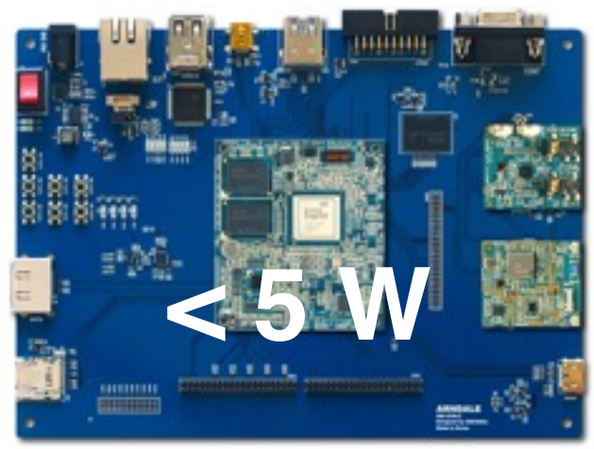
[Balaprakash 2013]: new parallel dynamic trees AL method for HPC. Compiler space MOMLO on runtime and power

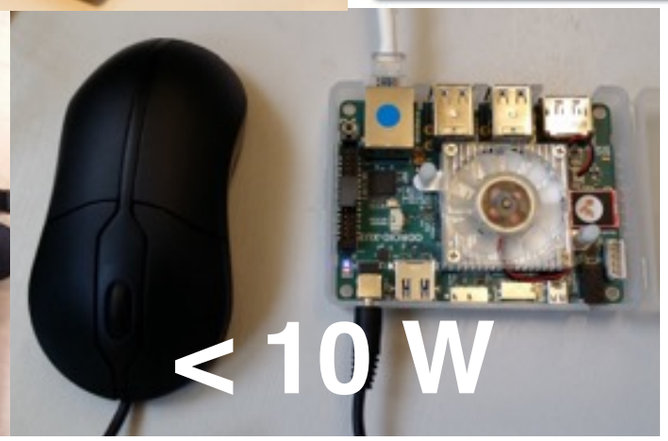


SLAMBench DSE: joint space exploration, multi-objective function, actual application, improvement in "performance"

Platforms

Machine names	TITAN	GTX870M	TK1	ODROID (XU3)	Arndale
Machine type	Desktop	Laptop	Embedded	Embedded	Embedded
CPU	i7 Haswell	i7 Haswell	NVIDIA 4-Plus-1	Exynos 5422	Exynos 5250
CPU cores	4	4	4 (Cortex-A15) + 1	4 (Cortex-A15) + 4 (Cortex-A7)	2 (Cortex-A15)
CPU GHz	3.5	2.4	2.3	1.8	1.7
GPU	NVIDIA TITAN	NVIDIA GTX 870M	NVIDIA Tegra K1	ARM Mali-T628-MP6	ARM Mali-T604-MP4
GPU architecture	Kepler	Kepler	Kepler	Midgard 2nd gen.	Midgard 1st gen.
GPU FPU32s	2688	1344	192	60	40
GPU MHz	837	941	852	600	533
GPU GFLOPS (SP)	4500	2520	330	60+30 (72+36)	60 (71)
Language	CUDA/OpenCL/C++	CUDA/OpenCL/C++	CUDA/C++	OpenCL/C++	OpenCL/C++
OpenCL version	1.1	1.1	n/a	1.1	1.1
Toolkit version	CUDA 5.5	CUDA 5.5	CUDA 6.0	Mali SDK1.1.	Mali SDK1.1
Ubuntu OS (kernel)	13.04 (3.8.0)	14.04 (3.13.0)	14.04 (3.10.24)	14.04 (3.10.53)	12.04 (3.11.0)





“Performance”: accuracy

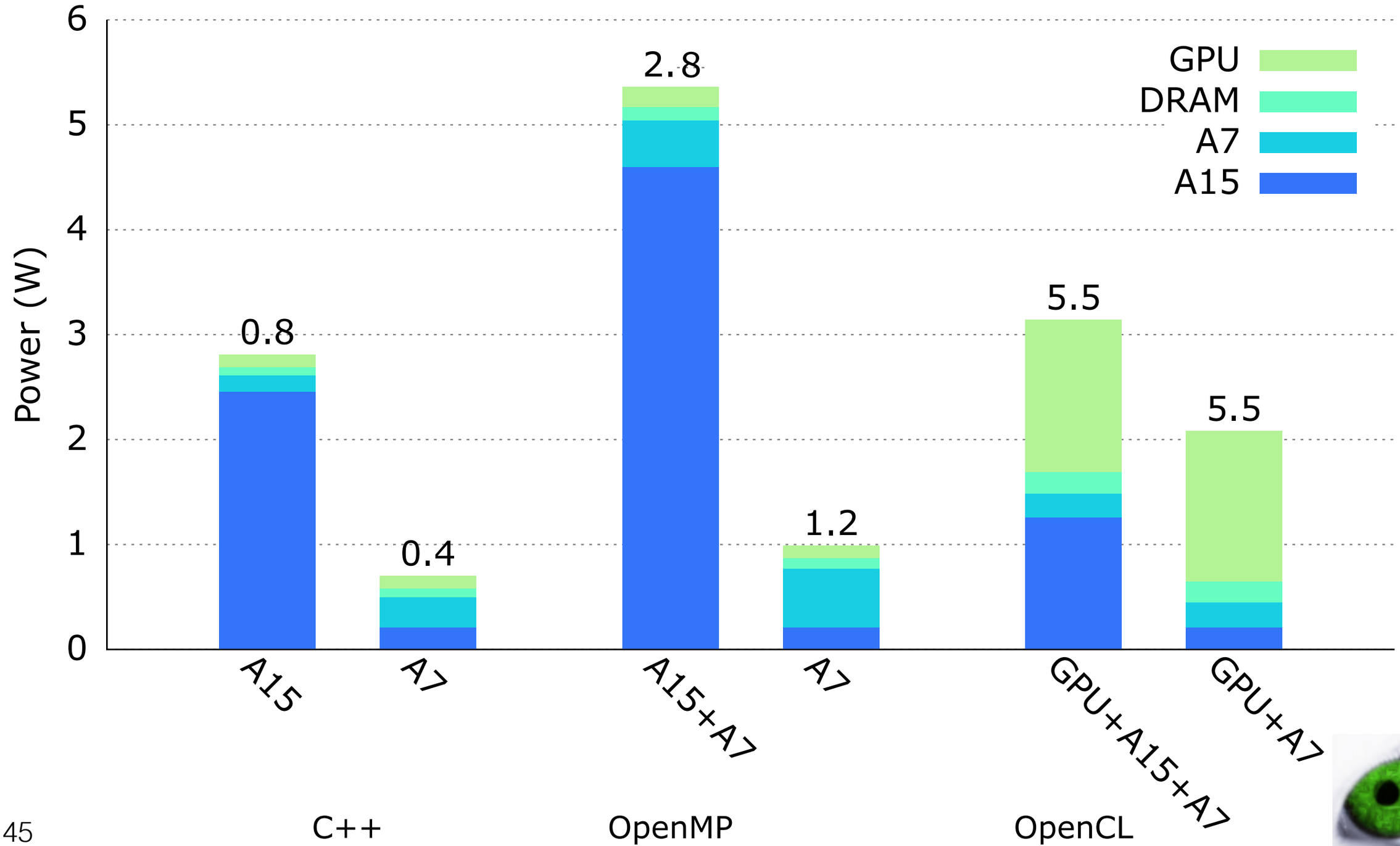
Absolute trajectory error (ATE) in cm - default algorithmic configuration

ATE in cm	TITAN	GTX870M	TK1	ODROID	Arndale
C++	2.07	2.07	2.06	2.06	2.06
OpenMP	2.07	2.07	2.06	2.06	2.06
OpenCL	2.07	2.07	n/a	2.01	2.07
CUDA	2.07	2.07	2.07	n/a	n/a

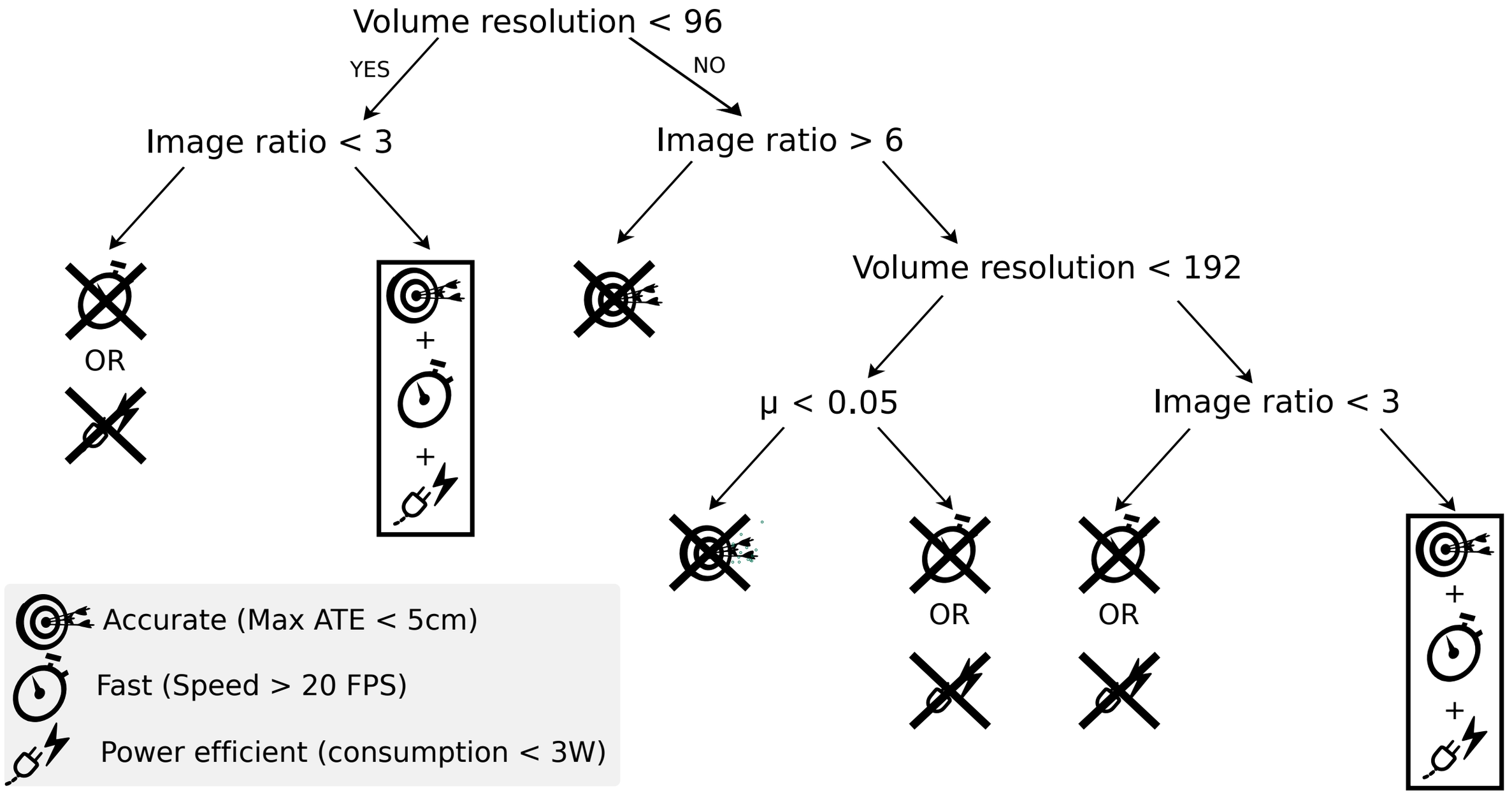
- ATE easy-to-use tool for non computer vision experts
- Semantic validation instead than bitwise accuracy

“Performance” power (ODROID-XU3)

On-board voltage/current sensors and split power rails:
power measured individually on big (A15), LITTLE (A7), GPU and DRAM



Predominant algorithmic features



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